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A Publication of the Society of Economic Paleontologists and Mineralogists
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Journal of Sedimentary Petrology

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 1, PP. 3–9, FIGS. 1–2, TABLES 1–4, APRIL, 1941

A HYDROMETER-PIPETTE METHOD FOR MECHANICAL ANALYSIS

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University of Wisconsin, Madison, Wisconsin

ABSTRACT

A small, sensitive hydrometer, reading in grams per liter, is enclosed within a pipette case similar to that holding the ordinary battery hydrometer. Pipette samples are taken from a suspension of known concentration as in the standard pipette method; instead of drying and weighing the samples, the concentration of the suspension in grams per liter is read from the hydrometer within the pipette case. The method is rapid and is well within the usual accuracy of sampling and dispersion. Since the pipette samples are taken from a known depth, and the hydrometer is immersed in a suspension which is uniform throughout, the faults of the Bouyoucos hydrometer method are eliminated.

The minimum equipment necessary for a rough analysis by this method is such that mechanical analyses of fine grained sediments could be made in the field. Such analyses would be designed to supplement, rather than replace, accurate laboratory analyses.

The extensive application in recent years of mechanical analysis to problems in the fields of geology, soils, ceramics, and engineering has led to the need for a rapid yet accurate method. The Bouyoucos hydrometer (Bouyoucos, 1927, 1936), graduated in grams per liter, has partially satisfied this need, and has gained wide usage. According to Bouyoucos* this hydrometer is now used in over 2000 laboratories throughout the world.

In using a Bouyoucos hydrometer, the soil is dispersed, and the suspension, after thorough mixing, is allowed to settle; at intervals, determined empirically by Bouyoucos, the hydrometer is placed in the suspension and readings are obtained in terms of the U. S. Bureau of Soils grade scale; they can be transposed into Wentworth units by plotting the results as a cumulative curve on semi-logarithmic paper.

For many soils, similar in size distribution to those soils on which the Bouyoucos hydrometer was calibrated, good results can be obtained by this method (Thoreen, 1933). That the results, however, are not universally satisfactory (Joseph, 1927; Keen, 1928; Olmstead, Alexander, and Lakin, 1931) is due to the following reasons:

1. The hydrometer rides at various depths in the suspension and thus does not measure the density of the suspension at a fixed point.
2. The hydrometer does not measure the density of the entire suspension because the suspension is not uniform.
3. Because of the large size of the hydrometer the suspension is disturbed when the hydrometer is placed in it. If the hydrometer is placed in the suspension at the beginning of the analysis and allowed to remain in the suspension throughout the analysis, sediment settles on the shoulders of the bulb and lower densities may be recorded than actually exist.

The chief objections to the Bouyoucos method are that the results are not always sufficiently accurate and that it cannot be used, without further empirical observations or calibration, to measure the size distribution in any but the U. S. Bureau of Soils grade sizes.

It is the purpose of this paper to describe a hydrometer-pipette method of mechanical analysis, which is designed to increase the rapidity of the pipette method by the utilization of a hydrometer. The authors wish to thank Dr. W. H. Twenhofel, Dr. Emil Truog, and Dr. R. J. Muckenhirn of the University of Wis-

* Personal communication, November 17, 1939.

N Y P L

consin for numerous criticisms and suggestions. Especial thanks are due to Rascher and Betzold, Inc. for their cooperation in making the hydrometer-pipette described in the following paragraphs.

THE HYDROMETER-PIPETTE

To provide a method for mechanical analysis comparing in speed with the Bouyoucos method and yet retaining the theoretical soundness of the pipette method, a hydrometer-pipette (fig. 1) has been designed similar to the ordinary battery hydrometer. The hydrometer is graduated in grams per liter (67° F., sp. gr. 2.65) in half gram divisions from −2 to 30 grams per liter. It is approximately 19 centimeters in over-all length; the bulb is 1.4 centimeters in diameter. The barrel of the pipette is approximately 28 centimeters in length and has an inside diameter of 1.9 centimeters to allow complete freedom of movement of the hydrometer. The stem of the pipette is 15 centimeters in length and is graduated in half centimeters linear distance measured from the tip. Both the hydrometer and the pipette are made of pyrex glass. The volume of sample necessary to float the hydrometer at its maximum immersion is approximately 35 cc.

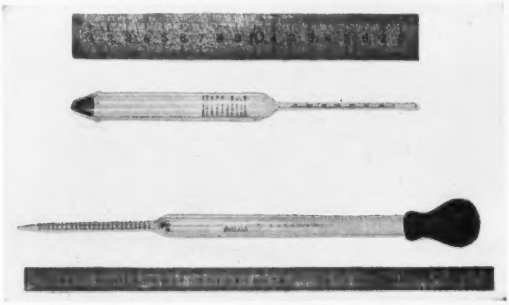

FIG. 1.—The hydrometer and the hydrometer enclosed in the pipette, as used in the hydrometer-pipette method of mechanical analysis.

The hydrometer-pipette thus makes possible a rapid pipette method conforming entirely with the principles of Stokes' law and not based on empirical observations. The resulting method differs from the standard pipette method only in that instead of drying and weighing the sample withdrawn from a known depth, as in the pipette method, the weight of the sample is determined directly by means of the hydrometer within the pipette.

The advantages of the hydrometer-pipette method over the Bouyoucos method are those of the standard pipette method, namely:

1. The density of the suspension is measured at a point to which particles of a given size will settle in a given time.
2. Little or no disturbance is created by the entrance of the stem of the pipette into the suspension.
3. The sampling time for any grade size may be computed directly from Stokes' law and does not need to be determined empirically as in the hydrometer method.

The only disadvantage of the hydrometer-pipette method compared to the Bouyoucos method is that the time required to complete an analysis is greater. For example, with the Bouyoucos hydrometer, fine clay (2 microns and less in size) is determined after a settling period

of two hours whereas in the hydrometer-pipette method it is determined after a settling period of 8 hours if the sample is taken from a depth of 10 centimeters. Although the analysis thus requires a longer time to complete, it does not require more of the analyst's time and this disadvantage cannot be considered serious.

The advantages of the hydrometer-pipette method over the pipette method are more or less obvious.

1. The time-consuming weighing and handling of beakers and aliquots is eliminated.
2. The results may be computed while the analysis is in progress. It is thus possible to determine how far it is necessary to carry the analysis to attain a good coverage of the size distribution of the particles.
3. Less steps are involved in handling the aliquots, therefore there is less opportunity for personal errors.
4. Less equipment is necessary (assuming that many analyses are to be run at once).

It is possible that where dispersion and sampling permit extremely accurate work the hydrometer-pipette method is not as accurate as the pipette method. However, for all practical purposes, the results of the analyses made thus far indicate that the method compares favorably with the original pipette method. The pipette method itself is subject to some errors and limitations, and these same errors and limitations will be found in the hydrometer-pipette method.

PROCEDURE FOR THE HYDROMETER-PIPETTE METHOD OF MECHANICAL ANALYSIS

The hydrometer-pipette method differs in only one essential detail from the standard pipette method, namely, that instead of drying and weighing an aliquot taken at a given time from a known depth in a suspension, as in the pipette method, the concentration of the aliquot is determined immediately by the hydrometer. For this reason the details of the dispersion procedure and directions for the preparation of samples are omitted in the following discussion.

Size of Sample.—The sample should be of sufficient size to provide 20 to 30 grams of combined silt and clay for analysis.

Preparation of Sample.—The sample is prepared for dispersion and dispersed according to standard procedures for the material at hand (Krumbein and Pettijohn, 1938). The coarse separates (particles coarser than silt) are removed by decantation, dry or wet sieving, and their weight determined by weighing. The fine separates (silt and clay) are made up to a liter with distilled water and placed in a straight sided container having a diameter of at least 2½ inches and a depth of 7 inches.

Analysis of Fine Separates.—The suspension is prepared by shaking and stirring after which its temperature is determined. If it is desired to determine the total amount of the fine separates in suspension at the beginning of the analysis, an initial reading may be made on a sample taken immediately after shaking. This sample should be taken from a depth of at least 15 centimeters; care should be taken to keep the suspension in the pipette well mixed. This aliquot may be returned to the suspension, which is then remixed.

The time of sedimentation of the coarsest separate to be determined is obtained from table 1. The correct sampling depth may be determined for the existing temperature of the suspension from table 2. A few seconds previous to the sampling time, squeeze the rubber bulb of the pipette, and insert the pipette to the desired depth and at the proper time withdraw a sample. Hold the pipette in a vertical position so that the hydrometer moves freely within the case and allow the hydrometer to come to rest. The suspension within the pipette may be kept mixed by occasionally allowing an air bubble to come up through the suspension. Read the hydrometer at the top of the meniscus and apply the proper temperature correction, obtained from the

TABLE 1. *Time required for spheres (sp. gr. 2.65) to settle 10 cm. in water (68° F.)*

Wentworth Grade Sizes		Atterberg Grade Sizes		U. S. Bureau of Soils Grade Sizes	
Diameter (mm.)	Time	Diameter (mm.)	Time	Diameter	Time
1/32 (0.312)	1 min. 56 sec.	0.02	4 min. 48 sec.	1/20 (0.05)	46 sec.
1/64 (0.0156)	7 min. 44 sec.	0.002	8 hrs.	1/200 (0.005)	1 hr. 16 min.
1/128 (0.0078)	31 min.				
1/256 (0.0039)	2 hrs. 3 min.				
1/512 (0.00195)	8 hrs. 10 min.				
1/1024 (0.00098)	32 hrs. 42 min.				
1/2048 (0.00049)	130 hrs. 50 min.				

TABLE 2. *Depth of sedimentation of spheres (sp. gr. 2.65) of grade sizes given above at the same time intervals, but at different temperatures*

Temp. (F.)	Depth	Temp. (F.)	Depth	Temp. (F.)	Depth	Temp. (F.)	Depth
50°	7.7 cm.	62°	9.2 cm.	74°	10.8 cm.	86°	12.6 cm.
51	7.8	63	9.3	75	11.0	87	12.8
52	8.0	64	9.4	76	11.1	88	13.0
53	8.1	65	9.6	77	11.3	89	13.1
54	8.2	66	9.8	78	11.4	90	13.3
55	8.4	67	9.9	79	11.5	91	13.4
56	8.5	68	10.0	80	11.7	92	13.6
57	8.6	69	10.2	81	11.9	93	13.7
58	8.7	70	10.3	82	12.1	94	13.8
59	8.8	71	10.4	83	12.2	95	14.0
60	8.9	72	10.6	84	12.3		
61	9.0	73	10.7	85	12.4		

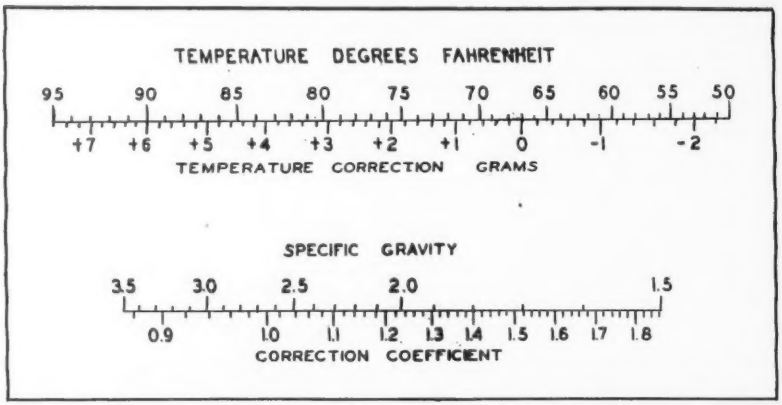
TEMPERATURE DEGREES FAHRENHEIT
95 90 85 80 75 70 65 60 55 50
+7 +6 +5 +4 +3 +2 +1 0 -1 -2
TEMPERATURE CORRECTION GRAMS
SPECIFIC GRAVITY
3.5 3.0 2.5 2.0 1.5
0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8
CORRECTION COEFFICIENT

FIG. 2.—Scales for temperature and specific gravity corrections, adapted from formulae furnished by Thoreen (1933). The temperature correction is added or subtracted to the hydrometer reading; the specific gravity correction is obtained by multiplying the hydrometer reading (grams per liter) by the specific gravity correction coefficient.

temperature correction scale (fig. 2). If a chemical dispersing agent was used make up a water solution having the same concentration of dispersing agent per liter as was used in the suspension; determine its concentration in terms of suspended material in grams per liter with the hydrometer and subtract this blank from each reading.

If the specific gravity of the material is known to differ from 2.65 determine the specific gravity correction coefficient (fig. 2) and multiply the previously corrected hydrometer reading by this factor. The resulting figure represents the concentration of material remaining in the suspension at the depth at which the sample was taken.

The first and subsequent aliquots may be returned to the suspension if care is taken not to lose any of the sample. If the aliquots are returned to the suspension, the suspension must be remixed.

The above procedure is repeated for each separate to be determined. It is desirable to redetermine the temperature of the suspension after long settling intervals.

Calculation of Results.—The results of the pipette-hydrometer analysis are computed in the following steps: (1) the weight of the coarse separate (sand) is determined by weighing; if an initial hydrometer reading has been taken the weight of the coarse separate may be found by subtracting the corrected reading from the total weight of the sample; (2) the weight of the first fine separate (coarse silt) is computed by subtracting the first corrected hydrometer reading from the total weight of the fine separates known after step (1); (3) the weight of the second fine separate is computed by subtracting the second corrected hydrometer reading from the first corrected reading. The amount of clay remaining in suspension at the sampling depth when the last reading is taken is represented by the final corrected hydrometer reading. The results may be converted into percentages of the total sample by dividing the weight of the separate by the weight of the total sample and multiplying by 100. A sample calculation follows:

	Grams
Weight of sample (determined by weighing)	32.57
Weight of sand (determined by weighing)	5.07
Total weight of silt and clay (by difference)	27.50
or	
Weight of sample (determined by weighing)	32.57
Total weight of silt and clay (corrected initial hydrometer reading)	27.50
Weight of sand (by difference)	5.07
Weight of total silt and clay	27.50
Corrected hydrometer reading of first fine separate	20.50
Weight of first fine separate	7.00
Corrected hydrometer reading of first fine separate	20.50
Corrected hydrometer reading of second fine separate	13.00
Weight of second fine separate	7.50
Weight of finest separate (final corrected hydrometer reading)	13.00

COMPARISON OF RESULTS OBTAINED BY PIPETTE AND HYDROMETER-PIPETTE METHODS

The results of eight analyses are shown in tables 3 and 4. The analyses in table 3 were made on different splits or sub-samples of the same samples and the Wentworth grade scale was used. Approximately 30 gram samples were used; the samples were dispersed with 50 cc. of ¼ normal sodium oxalate per liter in a milkshake machine. It is seen that the comparative results thus obtained are very close, and that the difference between the pipette and hydrometer-pipette values are little greater than the difference between the amount coarser than 1/16 mm. caught in wet sieving; in other words, the accuracy attained is comparable to the accuracy of sampling and splitting.

Table 4 shows four samples in which the U. S. Bureau of Soils grade sizes were used. These analyses were made on the same suspensions; the hydrometer-pipette analysis was made first and the

TABLE 3. *Comparison of results obtained by the pipette and hydrometer-pipette methods*

#	Method	>1/16 mm.	1/16–1/32	1/32–1/64	1/64–1/128	1/128–1/256	1/256–1/512	<1/512
1.	Pipette.....	39.4	24.7	17.8	7.1	3.4	2.3	5.3
1.	Hydr.-pipette...	39.0	26.4	16.6	6.7	4.5	2.0	4.5
2.	Pipette.....	1.3	21.4	29.2	22.2	13.8	7.2	4.8
2.	Hydr.-pipette...	0.7	19.8	29.8	23.0	14.4	7.4	4.7
3.	Pipette.....	4.7	37.0	31.5	9.9	4.3	3.3	14.1
3.	Hydr.-pipette...	3.5	34.0	31.5	10.6	4.0	4.0	11.0
4.	Pipette.....	12.8	16.3	12.7	10.9	8.0	6.2	33.0
4.	Hydr.-pipette...	10.8	20.0	13.3	10.0	10.1	6.3	29.0

samples were returned to the suspension. The pipette analysis was made in the usual fashion after the hydrometer-pipette analysis was completed. These results leave little to be desired and indicate that the hydrometer-pipette method gives results which are of the same order of accuracy as the pipette method.

POSSIBLE FIELD USE OF THE HYDROMETER-PIPETTE METHOD

The use of the hydrometer-pipette should extend the application of size analysis. Because much time is saved by its use more analyses can be made in the laboratory at no sacrifice to accuracy. In addition, it provides the field worker with a tool with which to make rough analyses of fine grained unconsolidated sediments. Depending on the accuracy desired and the equipment available, size analyses of fine grained sediments can be made with reasonable accuracy without a balance. It is only necessary to take a small amount of material (roughly a tablespoonfull if dry), make it up to a liter with water, shake, and then immediately take a sample at a depth of at least 15 centimeters. A corrected hydrometer reading on this sample gives the total weight of the sample. Unless distilled water is used a blank determination on the density of the water used should be subtracted from this and subsequent readings. The analysis may be made from this point on as in the usual laboratory method.

Obviously the method just outlined is only a very rough one and may be made with a fair degree of accuracy only when complete dispersion is either unnecessary or very easily attained. If complete dispersion is necessary, successful analyses may be made wherever electricity and dispersing apparatus are available. The initial hydrometer reading may be avoid-

TABLE 4

#	Method	>0.02 mm.	0.02–0.005	0.005–0.002	<0.002
5.	Pipette.....	17.8	20.0	19.2	43.0
5.	Hydr.-pipette....	17.3	20.9	18.5	43.3
6.	Pipette.....	27.0	29.5	9.3	34.2
6.	Hydr.-pipette....	26.0	30.7	10.0	33.3
7.	Pipette.....	41.2	33.8	7.7	18.3
7.	Hydr.-pipette....	39.3	34.1	8.3	18.3
8.	Pipette.....	23.0	29.5	13.3	34.2
8.	Hydr.-pipette....	21.7	30.6	12.7	35.0

ed if a rough balance, weighing to a tenth of a gram, is available.

Rough field analyses may serve a useful purpose where highly accurate results are unnecessary, where it is useful to have many approximate determinations rather than a few accurate analyses, or where it is impossible to collect and transport samples for laboratory study.

For example, much useful information on suspended loads could be determined in the field; the determination of the actual amount of material in suspension in grams per liter requires about two minutes time and no equipment except the hydrometer itself and a thermometer for use in determining the temperature correction. A size analysis could be made easily for it would not be necessary to make a dispersion. It would simply be useful to know the actual sizes of the particles as they occur in transportation.

Field analyses would be of value in connection with highway work, or other types of engineering investigations where only approximate analyses are desired.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 1, PP. 10–20, FIGS. 1–2, TABLES 1–3, APRIL, 1941

THE PROBABLE ERROR OF SAMPLING BEACH SAND FOR HEAVY MINERAL ANALYSIS

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and
United States Geological Survey, Washington, D.C.

ABSTRACT

Twenty-four closely spaced samples of beach sand were collected on a grid pattern and subjected to heavy mineral analysis. Each sample was sieved to obtain two grades, from which the heavies were separated in bromoform. Twelve splits of a composite sample made from quartered portions of the original samples were similarly treated. The data obtained were used to evaluate the sampling and laboratory errors of heavy mineral analysis, with the relation $E^2 = (e_1)^2 + (e_2)^2$, where E is the total observed error, e_1 is the sampling error, and e_2 is the laboratory error. The results showed that the average sampling error for the beach sand is about 10 per cent, but there is a particular sampling error associated with each mineral in the suite. The laboratory error of splitting, separating, and counting is of approximately the same order of magnitude as the sampling error. The individual observations show a fair agreement with the general theory of errors. An evaluation of current routines of heavy mineral analysis is made in the light of the data obtained.

INTRODUCTION

Several years ago the senior author evaluated the probable error of sampling beach sand for mechanical analysis (Krumbein, 1934). It may be expected, however, that each of the several characteristics of sediments, such as mean size, heavy mineral content, shape, and roundness, are subject to particular sampling and laboratory errors. The authors accordingly decided to apply the same method of study to the heavy mineral errors of the original samples.[1] The analytical data were obtained by the junior author; the senior author is responsible for the illustrations, the organization, and the method of presentation of the material.

Despite the increasingly quantitative nature of sedimentary work during the past decade, surprisingly few studies have been made of the errors to which the data are subject. In heavy mineral studies particularly, Dryden (1931) is virtually the only worker who has applied quantitative methods to the study of counting errors in heavy mineral analysis. Other recent studies which shed light on the errors of heavy mineral work are those of Tyler and Marsden (1937) and Grout (1937). The present paper extends the method of analysis used by Dryden to include the influence of the original sampling error on the final data, and attempts to evaluate other laboratory errors which are present in addition to the counting error.

The present study uses a common technique of heavy mineral analysis and evaluates the errors of that method for a particular set of beach sands. The study does not, therefore, isolate all errors involved in every heavy mineral study, although it does suggest that routine techniques may be improved. The method used involves the separation of two grades by sieving, the separation of the heavies in each grade with bromoform, and the counting of some 300 grains from each heavy mineral slide. In all, 64 slides were counted, and the particular errors for some two dozen mineral species were computed.

[1] The complete heavy mineral study was presented as a thesis for the degree of Master of Science at the University of Chicago by W. C. Rasmussen, 1939.

THE PROBABLE ERROR

Errors may be defined in various ways; for statistical studies most of them are based on the standard deviation. Among measures most widely used for evaluating errors is the probable error, which may be defined as that error which, in a given case, is exceeded by the errors of one half the observations. That is, the probable error represents the amount which must be added to or subtracted from the mean of the observations to obtain two extreme values between which there is an even chance that the true value lies. The probable error is specifically defined as

$$PE = 0.6745\sigma \qquad (1)$$

where σ is the standard deviation of the distribution. To assure rigor in the analysis, it is necessary that the distribution be normal, i.e., that the individual observations vary non-systematically about their mean value.

Within recent years, newer methods of evaluating errors have been developed, and some statisticians (Paterson, 1939, p. 23) consider the probable error as outmoded. Nevertheless, the probable error is useful for studies such as the present, because it does furnish an easily visualizd geometric picture of the error to which sedimentary data are subject.

When data are subject to a single error, the probable error may be expressed directly as such, or it may be expressed as the relative probable error, obtained by dividing its value by the mean value of the distribution, and multiplying the result by 100:

$$\%\ PE = 100(PE/M) \qquad (2)$$

where M is the mean of the observations. In this form the probable error indicates directly the per cent error of the observations; another useful form, which will also be used in the present study, is the probable error of the mean, PE_M, which applies to the mean value of n observations:

$$PE_M = PE/\sqrt{\ } \qquad (3)$$

The probable error of the mean is closely related to the "standard error" used by mathematical statisticians. The relation between the two is simply $PE_M = 0.6745\ SE$, where SE is the standard error. Thus in some instances at least it is possible to convert probable error data into their newer equivalents.

When several errors are present in a study, it is necessary to use a general theorem for the application of error equations. This generalization, expressed below, permits the independent evaluation of each error in the study. The use of the generalization is limited to instances in which the several errors are independent of each other, and in which they fluctuate non-systematically about their own mean.

Any sedimentary study is subject to a number of errors, of which two broad groups are most important. These are the errors of field sampling and the errors of laboratory investigation. The sampling error is a function of the homogeneity of the deposit, of the precise point of sampling, and of the method of sampling. The laboratory error is a function of the splitting, sieving, separation, and counting errors. For present purposes, it is adequate that these two broad types be distinguished, although it is possible to evaluate the individual errors in each group separately. Otto (1937) for example, showed that certain errors of laboratory splitting could be resolved into individual errors which were eliminated by a redesign of the apparatus. Otto's method of analysis involved the theory of control rather than the probable error.

In the present study, errors are classified either as belonging to the field error of sampling or to the laboratory error. The first error in the preceding list may be called e_1, the sampling error. The remaining errors may be grouped as e_2, the total laboratory error. The values of e_1 and e_2 are independent of each other, inasmuch as the first is a function of field methods in terms of the characteristics being studied, and the second is a function of laboratory methods.

When two or more independent errors are present, they do not combine as a simple arithmetic sum, but obey the rela tion

$$E^2 = (e_1)^2 + (e_2)^2 \qquad (4)$$

where E is the total observed error, and e_1 and e_2 are the independent errors, defined above. (Fisher, 1915, vol. 1, p.106.) A single analysis of any one sample for heavy minerals is subject to both independent errors, and its value is therefore influenced by E. A composite sample of a population, analyzed in the same manner, is subject to the laboratory error e_2, because the sampling error is held constant. By collecting a set of individual samples and analyzing each one separately, the total error E may be evaluated. A composite sample may then be made by mixing all the individual samples together, and from a number of analyses of the composite the laboratory error e_2 may be found. With these data, the sampling error e_1 may be computed with equation 4. It is essentially this method which is followed in the present study.

COLLECTION OF HEAVY MINERAL DATA

The samples used in this study are the same samples used by the senior author for his size study. The samples were collected on a rectangular grid from the Lake Michigan beach at Waverly, Indiana, as shown in figure 1. The samples were spaced 60 feet apart along the beach and 30 feet apart normal to the water line. A spot sample was taken at each of the grid points, and labelled as shown in the figure. In the laboratory a composite sample was prepared by quartering 50 grams from each individual sample, and mixing the splits thoroughly.

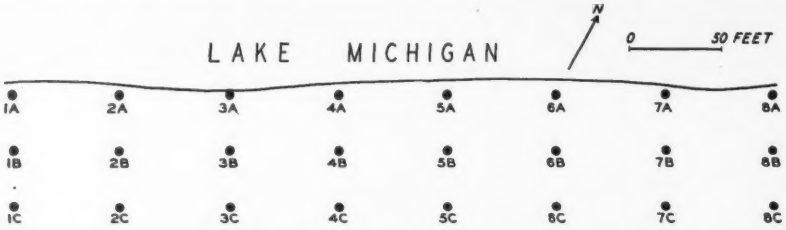

FIG. 1.—Grid used for collection of samples.

The detailed steps used in the laboratory study of the heavy minerals are summarized below:

1.—The 24 individual samples were quartered to 100 grams and sieved 10 minutes in a Ro-Tap to obtain two grades, 0.246–0.175 mm., and 0.175–0.124 mm. These two grades correspond to the $\sqrt{2}$ modification of Wentworth's grade scale.

2.—Eight samples of 100 grams each were quartered from the composite sample, and each split was sieved as in (1).

3.—Each sieve separate (two each from the 24 individual samples and two each from the eight composite splits) were separated into a heavy and a light fraction with bromoform (specific gravity = 2.85). The apparatus consisted of a glass funnel with a rubber tube and pinchcock, as illustrated in Krumbein and Pettijohn (1938, p. 335). The heavies in each instance were weighed and expressed as a percentage of the size grade. These data are given in table 1.

4.—The heavy minerals from each separation were quartered with a Microsplit (Otto, 1933) to an amount suitable for mounting on a microscope slide. Slides of each separate were made, yielding 64 slides in all.

5.—Approximately 300 mineral grains on each slide were counted. The mineral suite consisted of about two dozen species. The data were tabulated for each slide, yielding 64 sets of about 24 minerals each. These individual tally sheets were used in computing the various errors, in the manner to be described below.

The choice of particular grades for the heavy mineral studies was governed by

TABLE 1. *Weight percentages of heavy minerals*

Sample	0.175–0.124 mm.			0.246–0.175 mm.		
	Wt. of size grade, gms.	Wt. of heavies	% of heavies	Wt. of size grade, gms.	Wt. of heavies	% of heavies
1A	2.67	0.06	2.2	23.68	0.06	0.25
1B	5.34	.20	3.7	26.67	.09	.34
1C	6.75	.36	5.3	48.33	.24	.50
2A	2.93	.07	2.4	24.65	.06	.24
2B	5.47	.29	5.3	31.72	.19	.60
2C	4.30	.26	6.0	32.57	.21	.64
3A	3.20	.12	3.7	28.63	.20	.70
3B	6.21	.25	4.0	39.69	.19	.48
3C	6.23	.42	6.7	36.53	.26	.71
4A	4.79	.17	3.5	32.80	.12	.37
4B	7.72	.39	5.1	48.04	.27	.56
4C	4.24	.30	7.1	32.07	.21	.65
5A	6.18	.15	2.4	37.16	.13	.35
5B	7.99	.30	3.8	47.75	.21	.44
5C	5.16	.33	6.4	32.66	.23	.70
6A	7.62	.23	3.0	37.82	.13	.34
6B	9.33	.25	2.7	45.17	.18	.40
6C	4.53	.31	6.8	29.88	.20	.67
7A	3.89	.15	3.9	32.14	.12	.37
7B	7.89	.30	3.8	41.97	.20	.48
7C	6.03	.29	4.8	34.24	.21	.61
8A	1.62	.03	1.9	16.10	.03	.19
8B	6.45	.31	4.8	34.84	.14	.40
8C	4.29	.32	7.5	35.19	.20	.57
Composite	5.17	0.24	4.6	33.54	0.18	0.54
	4.84	.26	5.4	32.01	.18	.56
	5.34	.25	4.7	32.75	.18	.55
	4.96	.26	5.2	35.42	.19	.54
	5.21	.24	4.6	32.34	.17	.53
	5.23	.27	5.2	30.78	.18	.58
	5.53	.26	4.7	34.69	.18	.52
	4.87	.22	4.5	33.29	.17	.51

several factors. Complete mechanical analyses of the samples were already available, and it appeared that with so homogeneous a set of samples it would be adequate to choose two standard grades common to all the samples. In this manner the study would conform to a commonly used technique of heavy mineral analysis. The size data showed (Krumbein, 1934) that with only a few exceptions, the 0.246–0.175 mm. grade was adjacent to the modal class, and in the exceptions it was the modal class. Further, it seemed desirable to learn how the observational data varied among the several sizes, and consequently the next smaller grade was also used. Strictly speaking, therefore, the technique evaluated involves the use of a common size grade throughout; for practical purposes, however, the size grades may be considered to occupy approximately the same relative positions in the size distributions. Thus the data do not fully conform to Rubey's or Russell's rules (Rubey, 1933; Russell, 1936) for heavy mineral study, although they do approximate them.

The acid soluble minerals were not removed before the bromoform separation in the hope that data could also be obtained on their variations. It was found that the separation of dolomite and calcite was only partial, however, and so erratic that it strongly influenced the percentage distributions of the other min-

erals. Hence, a separate acid leaching was performed on duplicate samples, and corrections were applied to the weights of the heavies recovered, in accordance with the abundance of acid solubles in the heavy mineral slides. The dolomite and calcite were accordingly not counted in the final analysis of heavies, and the figures of table 1 are for the acid-leached samples.

TABLE 2. *Calculation of errors for metamorphic amphibole, 0.175–0.124 mm. grade*

Sample	Frequency Per cent	Deviation (d)	Deviation squared (d^2)
1A	35.6	+3.8	14.44
1B	25.5	−6.3	39.69
1C	29.3	−2.5	6.25
2A	38.3	+6.5	42.25
2B	23.5	−8.3	68.89
2C	37.7	+5.9	34.81
3A	32.2	+0.4	.16
3B	31.4	−0.4	.16
3C	30.2	−1.6	2.56
4A	29.2	−2.6	6.76
4B	32.0	+0.2	0.04
4C	29.7	−2.1	4.41
5A	35.5	+3.7	13.69
5B	34.8	+3.0	9.00
5C	29.0	−2.8	7.84
6A	32.4	+0.6	.36
6B	32.3	+0.5	.25
6C	29.3	−2.5	6.25
7A	30.4	−1.4	1.96
7B	35.7	+3.9	15.21
7C	34.5	+2.7	7.29
8A	38.8	+7.0	49.00
8B	26.1	−5.7	32.49
8C	30.5	−1.3	1.69
Total	763.9		365.45
Composite	28.4	−3.7	13.69
	31.5	−0.6	.36
	39.0	+6.9	47.61
	36.1	+4.0	16.00
	28.7	−3.4	11.56
	31.2	−0.9	.81
	31.5	−0.6	.36
	30.4	−1.7	2.89
Total	256.8		93.28

Another variable which caused trouble was the presence of so-called "altered grains" in the slides. As work progressed it was found that an increasing number of these grains could be identified, which necessitated reclassifying some of the earlier counts. At best, however, some 40 per cent of altered grains remained in the 0.246–0.175 mm. grade, and about 30 per cent were present in the 0.175–0.124 mm. grade.

CALCULATION OF THE SAMPLING ERROR

The amount of data obtained from the study is too voluminous to be published in full.[2] For each size grade data are available on the number percentage frequency of the entire suite of heavy minerals. These frequencies are shown for the 24 individual samples and for the eight composite samples. The mean and the standard deviation of the 24 individual samples furnish the value of the total error E of that mineral, and the mean and standard deviation of the composite furnish the value of the laboratory error e_2 of the same mineral. From these two numbers the field sampling error e_1 was computed for the mineral by means of equation (4). In all, such sets of errors were determined for each of the two dozen minerals comprising the suite, for both chosen size grades. An illustration will indicate the steps involved. Table 2 shows the sample numbers in the first column; the number percentage frequency of metamorphic amphibole is in the second column; the deviation of this percentage from its mean (31.83 per cent) is listed in the third column; and the square of the deviations are given in the fourth column. The lower eight samples are from the composite. The sum of the squared deviations is used to compute the standard deviation with the equation:

$$\sigma = \sqrt{\sum d^2/n} \qquad (5)$$

For the 24 individual samples this value is $\sigma = \sqrt{365.45/24} = 3.90$; for the composite the value is $\sigma = \sqrt{93.28/8} = 3.41$. The probable errors in each case are found by equation (1); for the 24 samples

[2] Interested readers may apply to the General Library of the University of Chicago for a loan of the original thesis.

it is $PE = (0.6745)(3.90) = 2.63$; for the composite it is $PE = (0.6745)(3.41) = 2.30$.

The relative errors in each case are found by dividing the probable error by the average of the set according to equation (2). For the 24 individual samples this is $\%PE = 2.63/31.83 = 8.26$ per cent; for the composite it is $\%PE = 2.30/32.1 = 7.17$ per cent. The error of the individual samples represents the total error E, and that of the composite represents the laboratory e_2. Hence $E = 8.26$; $e_2 = 7.17$. Substitution in equation (4) yields

$$(8.26)^2 = (e_1)^2 + (7.17)^2$$

from which the sampling error is $e_1 = 4.10$ per cent. Thus for the metamorphic amphibole in the 0.175–0.124 mm. grade, the field sampling error is 4.1 per cent and the laboratory error is 7.17 per cent. This mineral comprises 31.8 per cent of the total heavy mineral suite in the 0.175–0.124 mm. grade.

Similar computations were made on each of the other minerals for both size grades. The summarized results are given in table 3. The example just mentioned is the first item in the table. In some instances the field sampling error is not shown. These blanks represent minerals so rare in the suite that the errors become large and erratic, so that the use of equation (4) yields imaginary values for e_1. Theoretically this should be impossible but actually when the number of grains is very small the counting error becomes so large that eight or 24 samples are not sufficient for its determination.

TABLE 3. *Summarized error data of heavy minerals (values expressed in number percentages)**

Mineral	0.175–0.124 mm.				0.246–0.175 mm.			
	Mean Frequency 24 Samples	Total Error E	Field Error e_1	Lab. Error e_2	Mean Frequency 24 Samples	Total Error E	Field Error e_1	Lab. Error e_2
Met. Amphibole..	31.83	8.3	4.1	7.2	35.50	3.9	2.5	3.1
Diopside.....	1.25	32.9	17.3	28.0	1.17	29.1	13.5	25.8
Kyanite.....	0.31	77.0	—	113.0	0.04	167.0	—	—
Epidote.....	8.20	13.7	10.9	7.3	3.83	27.4	22.1	16.2
Garnet.....	7.19	30.4	29.2	8.3	1.05	59.2	55.6	20.3
Staurolite.....	0.43	60.0	32.0	51.0	0.08	119.0	—	176.0
Tourmaline.....	0.79	35.0	—	54.0	0.38	73.0	—	89.0
Andalusite.....	0.33	54.0	—	176.0	0.09	144.0	—	—
Sillimanite.....	0.48	51.0	—	87.0	0.18	86.0	—	176.0
Rutile.....	0.44	49.0	29.0	40.0	0.11	135.0	3.6	130.0
Iron Ores.....	10.02	15.7	5.2	14.8	11.56	15.5	6.4	14.1
Leucoxene.....	2.21	31.8	16.5	27.2	1.88	32.4	18.1	26.9
Hypersthene.....	1.37	28.9	—	31.4	0.43	73.0	58.0	44.0
Augite.....	1.26	33.8	23.0	24.8	0.72	51.0	40.0	31.0
Bas. Hornblende.	2.06	35.9	31.0	17.9	0.58	48.0	—	75.0
Zircon (round)...	0.30	75.0	—	128.0	—	—	—	—
Zircon (euhedral).	0.20	73.0	—	74.0	0.01	320.0	—	—
Titanite.....	1.04	43.0	25.0	35.0	0.30	66.0	—	100.0
Apatite.....	0.88	33.0	—	47.0	0.21	84.0	—	91.0
Muscovite.....	0.04	167.0	—	167.0	0.04	178.0	—	—
Biotite.....	0.06	71.0	—	—	—	—	—	—
Altered Grains...	29.40				41.50			

* The data are given to three or four significant figures because the mean frequencies are based on a total count of about 8000 grains.

DISCUSSION OF THE ERRORS

FIELD SAMPLING ERROR

The values in table 3 show a wide spread in the sampling errors for the individual minerals, ranging from 2.5 to 58 per cent. There is a relation between the

frequency of a particular mineral and its sampling error, insofar that the larger errors are associated with the smaller frequencies. It is possible to define an average sampling error for the entire suite by taking a weighted arithmetic mean probable error in terms of the total error E and the laboratory error e_2, and substituting the average values in equation (4). The weighted averages are computed by multiplying the relative errors of each mineral (equation 2) by the mean frequency of that mineral, summing these values, and dividing the total by the sum of the mineral frequencies. The resulting expression simplifies to that on the right:

$$\text{Average error} = \sum[(PE_i/M_i)(M_i)]/\sum M_i = \sum(PE_i)/\sum M_i \qquad (6)$$

where PE_i is the probable error of a particular mineral, and M_i is its mean frequency; the sigma indicates summation. Application of equation (6) yields the following weighted averages:

Mean field sampling error, 0.175–0.124 mm. = 12.3 per cent

Mean field sampling error, 0.246–0.175 mm. = 9.0 per cent

In contrast to this average sampling error of about 11 per cent for both size grades of the heavy minerals, the earlier size study showed a sampling error of only 4.5 per cent for the median grain diameter (Krumbein, 1934). Thus, the sampling error for heavy minerals in these samples is more than twice as large as that for mean grain size. Geometrically this would mean that the sand is more homogeneous with respect to average grain size than to average heavy mineral content. The data at hand do not tell the whole story, however, because in their present form the two errors are not entirely comparable.

In computing errors with respect to mean size the entire size distribution was used, and this distribution was summarized in terms of a single parameter, the median. In heavy mineral studies, it is inevitable that only a small fraction of the sediment (less than 1 per cent of the sample) is used for heavy mineral analysis. Moreover, the heavies are taken from one or two size grades only, and do not represent the entire heavy mineral distribution. The present sampling error is more nearly comparable to the error of sampling sands for their 0.246–0.175mm. size percentage. In that case, it may be expected that a higher degree of variability would enter the size analysis, inasmuch as only a single grade would be considered. It is generally true that the variation of a sub-sample is larger than the variation of the entire sample.

In addition to the use of sub-samples for heavy mineral work, the computations are based on number frequencies instead of weight frequencies. The sampling error for the observed weight-percentages of heavy minerals in the samples (data from table 1) yields the following values:

Mean weight-per cent sampling error, 0.175–0.124 mm. = 24.3 per cent

Mean weight-per cent sampling error, 0.246–0.175 mm. = 21.5 per cent

This lack of agreement between total weight data and counting data was noted by Grout (1937) in his study of heavy accessories in igneous rocks. It was found that without centrifuging, the amount by weight of heavies obtained varied widely, and yet the ratios of the several minerals in the separate remained fairly constant. Another factor which enters the beach study is a linear variation in the heavy mineral distribution over the beach. That is, the A-row of samples has in general a lower percentage of heavy minerals than the B-row, and that in turn is lower than the C-row. This apparent trend in the data influences the observed errors because the application of error theory is only approximate unless the distribution of heavy minerals is random over the beach. A discussion of the linear patterns on the beach will be given in a subsequent paper by Rasmussen.

Practical limitations to heavy mineral work dictate the greater feasibility of separating the heavies from one or two grades, rather than from the entire size

range of the sample. This is particularly true of sands having a large size range, in which the larger grains interfere with the uniform mounting of the heavy separate; moreover, there are more altered grains in the larger sizes. Among ancient sands, such as the St. Peter, it is possible to separate the entire heavy mineral suite without difficulty, so that the sampling error may in some instances be materially reduced. It appears from this study, however, that the use of a single size grade for heavy mineral work will involve an appreciable sampling error for individual samples.

Sampling theory permits an attack on this aspect of the problem, however, by the use of compound samples in terms of equation (3). It was earlier pointed out (Krumbein, 1934) that compound samples prepared by mixing four closely-spaced samples reduce the sampling error by approximately one-half, and mixtures of 10 samples reduce it to about 0.3 of the error of a single sample. That is, the error of the mean of a set of observations varies inversely as the square root of the number of samples, according to equation (3). It is suggested, therefore, that heavy mineral sampling procedures include the collection of mixtures of at least four samples each. For example, if samples of river sand are to be collected at intervals of a mile along a stream, the procedure would involve collecting four closely-spaced samples at each sampling site, and combining the four into a single unit for laboratory analysis. The distance between the samples in each composite should be negligible in comparison with the distance between main samples. In the instance given, the four samples of each composite could be collected at the corners of a five- ten- or twenty-five-foot square, depending on the homogeneity of the deposit.

THE LABORATORY ERROR

Table 3 includes the laboratory error for each mineral, computed directly from the composite sample. This error varies from 3 per cent to more than 100 per cent, the latter associated with the smaller frequencies. It should be borne in mind that the determination of these errors is only approximate, because several assumptions are involved in the analysis. The theory of the method itself includes the assumption that the population sampled represents essentially the entire universe of grains, so that in the composite sample the sampling error itself is held constant. This assumption is only partially satisfied inasmuch as a comparatively small number of samples is used in the entire study. The number 24, in fact, was chosen because statisticians generally agree that it is the minimum number to which general statistical theories may be applied.

As in the case of the sampling errors, an average laboratory error may be had by computing a weighted mean (equation 6). Such a weighted average yields the following values:

Mean laboratory error, 0.175–0.124 mm. = 13.2 per cent
Mean laboratory error, 0.246–0.175 mm. = 10.8 per cent

The average of these two values is approximately equal to the average field sampling error given earlier. This 1:1 ratio between sampling and laboratory errors in heavy mineral analysis contrasts strikingly with the 8:1 ratio of sampling to laboratory error found in the previous size study of the same sands. Part of the explanation for the difference lies in the greater complexity of heavy mineral analysis, which includes the operation of sieving as only one of its preliminary steps.

In detail, the laboratory operations involved in the heavy mineral studies include the following steps: Quartering the field sample into a test sample; sieving the test sample into size grades; heavy mineral separation with bromoform; micro-splitting the heavy separate; mounting the quartered heavies on a microscope slide; and counting and tabulating the mineral grains. It may be seen that the size analysis includes only the first two steps, and that errors of varying mag-

nitude may enter the additional stages of heavy mineral work. An approximate analysis of these several errors was made by an extension of equation (4), in which the square of the total laboratory error equals the sum of the squares of the several individual laboratory errors. A detailed study of these errors would involve the development of an experiment in which each factor is separately isolated, but it is believed that the order of magnitude of the separate errors at least is disclosed. The analysis involved first the evaluation of the splitting and sieving errors as a unit, followed by the use of equation (4) to isolate the remaining laboratory errors. Data from the bromoform separations permitted a further division of errors, with the result that three groups were approximately evaluated. These are given here to indicate the relative orders of magnitude:

Laboratory error of splitting and sieving	$1.0 \pm 0.5\%$
Laboratory error of bromoform separation	$3.5 \pm 1.0\%$
Laboratory error of microsplitting, mounting, and counting	$10.5 \pm 2.0\%$

These values approximately satisfy the relation

$$(e_t)^2 = (e_s)^2 + (e_b)^2 + (e_c)^2 \qquad (7)$$

where e_t is the total laboratory error, e_s is the error of splitting and sieving, e_b is the error of bromoform separation, and e_c is the error of microsplitting, mounting, and counting.

The analysis just given suggests that the errors of the fourth and sixth steps above are the largest, and among these it is believed that the counting error itself is of prime significance. The theory of counting (based ultimately on equation 3), is that the error is equal to the reciprocal of the square root of the number of items counted. That is,

$$e = k/\sqrt{} \qquad (8)$$

where k is a constant. To avoid confusion regarding the nature of the counting error, it should be pointed out that the term does not imply an arithmetic error on the part of the worker, but refers instead to sample size. That is, if a slide of 300 grains is correctly identified and counted, the data are still subject to the counting error because the given slide represents only one count of 300 out of an infinite number of possible counts of 300. Thus the counting error is an estimate of the error which may be expected in a single count of 300 grains. As the number of items counted increases, the counting error decreases in accordance with equation (8).

If the counting error is of major importance in the heavy mineral study, the laboratory error data, plotted against the frequency of individual mineral species, should show substantial agreement with equation (8). Figure 2 shows the result, and indicates a good approximation. The hyperbolic nature of equation (8) indicates that it will graph as a straight line with slope -0.5 on double log paper. The abcissae of figure 2 represent the percentage frequencies of the minerals, and the ordinates are the percentage laboratory errors from table 3. The heavy line in the graph is the straight line of approximate best fit, and the dashed line is the theoretical line of equation (8). The slope of the heavy line is -0.56, yielding the empirical relation $e = k/n^{0.56}$ instead of $e = k/n^{0.50}$ as theory demands.

The agreement of the laboratory errors with the law of counting supports Dryden's earlier findings (1931) of the effect of the number of grains counted on the accuracy of heavy mineral analysis. On the assumption that the heavy line may be used as an approximate evaluation of the errors, it may be seen that in order to have an accuracy within 10 per cent, it is necessary that approximately 27 grains be present, which corresponds to a mineral frequency of nine per cent in a count of 300 grains. For a five per cent accuracy, it would be necessary to have approximately 90 grains present (30 per cent of a count of 300 grains). The corresponding values given by Dryden, and based on equation (8) directly, are 32 grains and 125 grains, respectively. The orders of magnitude are roughly the same.

The departure of individual points in figure 2 from the theoretical straight line of equation (8) is due to other factors which enter the errors. The general agreement of trends suggests, however, that the counting error as defined earlier is the largest single factor. This implies that those minerals least abundant in the suite are subject to the largest errors, and are, from a strict statistical point of view, of least significance in correlation. Geologically, however, the rare minerals may be of considerable significance, as numerous workers have pointed out. It is not safe, however, to compare absolute or relative frequencies of the rarer minerals from sample to sample without taking cognizance of the fact that the error of counting may be large and variable.

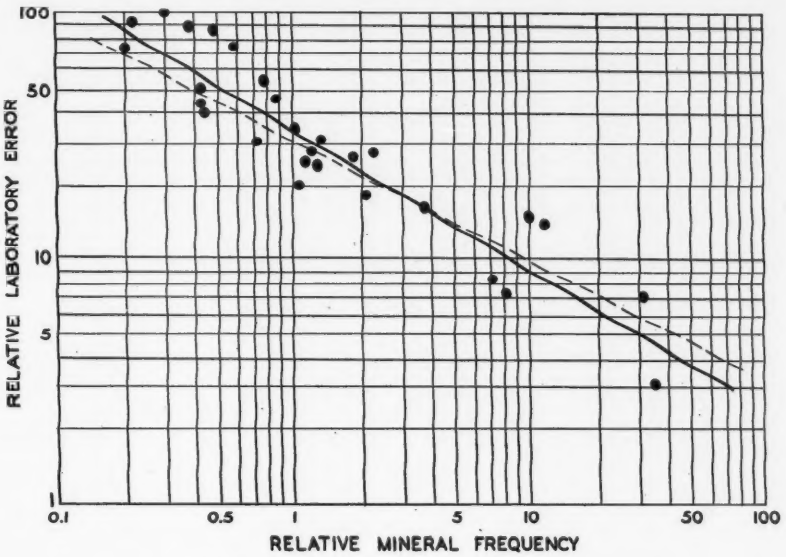

FIG. 2.—Relation between relative grain frequency and magnitude of the total laboratory error. (Data from table 3.)

SUMMARY AND CONCLUSIONS

The fact that heavy mineral studies have proved successful in the correlation of deposits and in the study of mineral provenance argues that the technique amply justifies itself, despite the apparently large errors to which it may be subject. It can, therefore, be expected that if routine methods of heavy mineral study can be improved to decrease the errors to comparatively small values, heavy mineral analysis should prove applicable to studies which are too complex for present techniques.

In this connection, recent work by Rittenhouse (1939) offers a possible solution of some of the problems. He proposes that heavy minerals in water-laid deposits be compared by their hydraulic ratios, i.e., the amount by weight of a species of heavy mineral to the amount by weight of light minerals of equal hydraulic size. His proposal is based on the principle that this ratio remains constant for any given size regardless of the degree of sorting or the average grain size of the

samples, but will be modified by contamination and other factors. Inasmuch as some of the field error in the present set of samples appears to be due to the difference in sorting and average grain size over the beach, use of Rittenhouse's method might result in some reduction of this error. When the degree of sorting or mean grain size has a greater variation, the proposed method may be even more useful.

The laboratory errors may not be strongly affected by improvements such as those suggested if it is true that the counting error is the largest factor in the laboratory error. The error of counting can apparently be reduced only by counting additional grains. Dryden showed (1931) that the reduction of the counting error to a reasonable value for rare minerals involved more effort than can be justified by the results.

A recent suggestion by Grout (1937), however, offers a solution of the difficulty. In a study of accessory minerals of igneous rocks it was shown that accurate ratios of the rarer accessory minerals were obtained by identifying and tabulating only those mineral grains, but at the same time keeping count of the total grains present. In Grout's method this included fractionating some of the flood minerals magnetically. In some such manner, a very large number of grains may be taken into consideration, with the result that the important rare minerals are counted in sufficient abundance to reduce the counting error to a small value. For example, if it is decided from the nature of the study that the ratio of garnet to hornblende is the significant value to be obtained, and if these minerals are present to the extent of about five per cent each in the total suite, one may determine the proportion of these two minerals in a total count of 2000 or more grains, by grouping all other minerals in a "flood" category. Five per cent of 2000 is 100 grains, which is not an unduly large number to identify and count. Such a procedure reduces the counting error of the two important minerals to the order of about five per cent. Such a method is already being used by Rittenhouse in the study of river sand.[3]

ACKNOWLEDGMENTS

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 1, PP. 21–27, FIG. 1, TABLES 1–2, APRIL, 1941

NEAR SHORE CORAL LAGOON SEDIMENTS FROM RAIATEA, SOCIETY ISLANDS

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ABSTRACT

Sediments from the Raiatea lagoon are strikingly uniform in mineralogical and mechanical composition. They are composed almost exclusively of comminuted coral reef fragments, and are well sorted sands of very coarse to medium grain size. Comparison with other coral lagoon sediments from the Pacific indicate marked absence of terrestrial material, and a tendency for the size frequency curves to be skewed in a negative phi direction due to absence of silt and clay particles.

The study of sedimentary processes as a special subject, in spite of many important contributions of the last several years, remains largely in the fact-finding stages. The present report on bottom sands from tropical coral-reef enclosed lagoons adds new data to the growing knowledge of such sediments and the results of the study are correlated end compared with similar studies on record.

The samples were collected by the senior author in the Summer of 1939 during the geological mapping of the Leeward Islands of the Society Archipelago (Stark and Howland). Grateful acknowledgments are made to Mr. R. Sholtz of Uturoa, Raiatea, who generously supplied a boat and constructed in his shop a bucket for collecting samples. Laboratory work has been done in the laboratory of Northwestern University.

GENERAL GEOLOGY

Raiatea and Tahaa are central islands in the Leeward group of the Society Archipelago, west longitude 151° 30′ and south latitude 16° 45′. Like other islands in this archipelago, they are highly dissected tops of extinct volcanoes, which rise over 12,000 feet from the ocean floor. Tahaa, roughly circular in outline, has a diameter of 8 miles, and pear-shaped Raiatea is 15 miles long by 9 miles at its broadest width. Maximum elevations on Raiatea and Tahaa attain 3389 and 1936 feet respectively. The two islands were formed more or less simultaneously; they are surrounded by a common barrier reef and show striking analogies in the composition of their basic lava flows, radial dikes, and ejectamenta. Davis (1928) visited the islands in 1914 and from a study of the spur slopes estimated that subsidence since cone-building must have been at least 1000 feet. Since the maximum depth of the reef-enclosed lagoon between Raiatea and Tahaa is less than 150 feet, and the distance between the islands is barely four miles, there is no doubt that the two peaks formed a single island throughout their early history.

Surrounding each of the islands is a wave-cut bench ranging in width from a few feet to a mile; although extremely irregular, the average width is about 2000 feet from strand line to the foot of the ridge spurs (fig. 1). The beaches rise from the shore gradually to elevations of 3 to 4 feet. Similar flats around Tahiti, Moorea, and Borabora have been cited as evidence of recent lowering of sea level rather than ubiquitous uplift of the various islands. The flats are covered with a mixture of coral sand, fragments of coral stems, shells and shreds of organic material, and a very small quantity of volcanic material. Near the base of the ridges (outside of the valleys) the mantle rock is rarely more than a few inches thick but increases in depth as the lagoon is approached, and at the strand line there is commonly 3 to 4 feet of loose sand above

the coral reef basement. In the broad, maturely opened valleys, igneous debris from the highlands covers the calcareous mantle and builds up gently sloping alluvial cones into which the streams have cut narrow gorges.

Fringing reefs extend from the shores and range in width from a few feet to a half mile. The waters above the fringing reefs rarely exceed 3 to 4 feet in depth. Near shore thick sands of coral and shell debris with more or less admixture of organic material cover the reef platform. The sands thin out as the seaward edge of the fringing reef is approached and only sparse fragments of coral stems and bits of shells cover the areas adjacent to the deep water of the lagoon.

Separated from the fringing reef by the deeper water is a well developed barrier reef which surrounds Raiatea and Tahaa in the form of a figure 8 (fig. 1). The outer edge of the barrier averages about a mile distant from the strand line although there are many variations due to the irregularities of the shore line. The barrier reef is continuous except for narrow passes, two in the Tahaa reef, and eight in the Raiatea reef. These passes are opposite prominent embayments in the shore line which represent drowned mouths of valleys. None of the passes is more than a quarter of a mile wide. All may be used by small boats but only six have been charted for navigation. Small reef islands occur in all but two of the passes.

Points selected for collection of samples from ridge spurs to the outer edge of the fringing reefs were chosen where there would be the least interference from stream-valleys and are shown on figure 1.

COMPOSITION OF THE SEDIMENTS

Sediments from the shoreward portion of the Raiatea lagoon are strikingly uniform in composition irrespective of the locality of sampling. Samples from the lower, subaerial section of the beach and from the shoreward portion of the lagoon are identical in composition. All of the sediments consist of comminuted limestone reef fragments and certain other associated substances described below. Individual grains composing the sands are extremely angular and commonly have sharp, protruding corners or edges whose presence suggests limited transportation of the material. Coarse material which is present consists exclusively of fragments of coral and broken pelecypod shells 1 to 2 cm. long. Material of granule and very coarse sand size commonly contains ellipsoidal-shaped faecal pellets of rather uniform dimensions (2–3 mm. long, 1 mm. wide). Such pellets are not distributed uniformly and at maximum constitute about one per cent of the sample, but appear more or less at random in samples taken 100 or more feet seaward from the strand-line. Nearer shore the pellets are absent probably because they are destroyed by wave action. The pellets consist of very fine sand and silt rather poorly cemented by a gelatinous substance secreted in the alimentary canals of organisms. Locally the bottom sediments are cemented into thin crusts unlike faecal pellets except in the common association of the two and in the fineness of the material composing them. The crusts consist of fine sand and silt cemented with clay particles and are formed during periods of quiet water in the lagoon. Later they are broken into flakes by gentle wave action. The source of much of the fine sediment from which the crusts are made is probably derived from disintegrated faecal pellets, hence the common association of the two.

The sediments are teeming with shelled organisms; tiny gastropods ranging from $\frac{1}{2}$ to 1 mm. in length constitute 5 per cent or the coarse sand in some samples. Fragments of echinoid spines, and spicules of sponges and holothurians are also abundant. In sizes less than $\frac{1}{2}$ mm., particularly in the fine sand size, foraminifera are numerous. In the fine sand and silt sizes there is also much dark gray and black colored calcareous material which apparently is darkened by organic matter. The silt size frequently contains from 50 to 60 per cent of dark colored fragments which

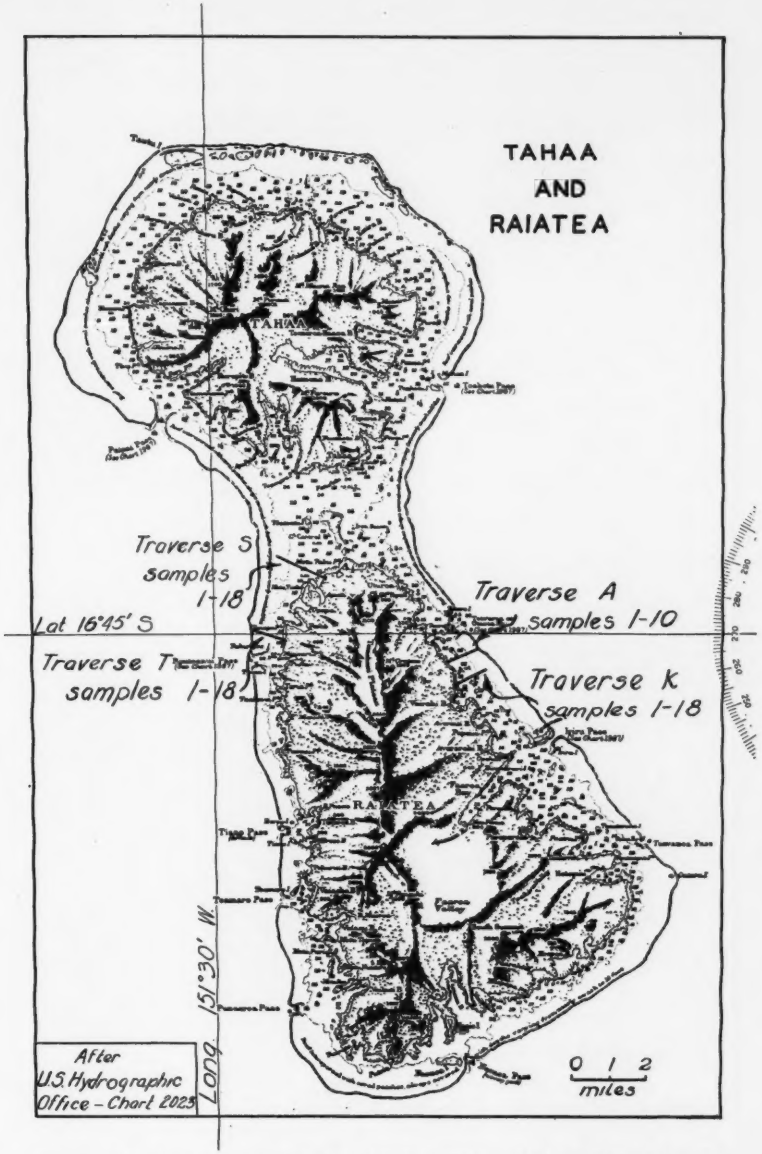

FIG. 1.—Islands of Tahaa and Raiatea showing position of the localities of sampling.

TABLE 1. *Statistical constants of samples of beach and lagoon sediments, Raiatea*

Sample	Q_3 (mm.)	*Md* (mm.)	Q_1 (mm.)	$QD\phi$	$Skq\ \phi$	Distance from shoreline
K3	.795	.319	.180	1.09	−.05	25 ft. inland
K4	.400	.235	.164	.65	−.12	shoreline
K5	.690	.240	.152	1.10	−.42	25 ft. seaward
K6	.590	.249	.135	1.40	−.17	55 ft. seaward
K7	.695	.285	.153	1.10	−.19	80 ft. seaward
K8	.980	.433	.209	1.15	−.05	105 ft. seaward
K9	.930	.410	.214	1.08	−.12	130 ft. seaward
K10	.810	.320	.185	1.09	−.27	160 ft. seaward
K11	.600	.275	.170	.93	−.21	185 ft. seaward
K12	.670	.300	.185	.92	−.22	210 ft. seaward
K13	.739	.310	.185	1.00	−.25	240 ft. seaward
K14	.710	.325	.198	.92	−.21	265 ft. seaward
K15	.670	.284	.183	.95	−.30	290 ft. seaward
K16	2.35	.840	.380	1.33	−.16	320 ft. seaward
K17	11.00	3.40	1.28	3.15	−.14	340 ft. seaward
K18	.670	.272	.165	1.02	−.21	370 ft. seaward
T1	.555	.290	.177	.89	−.11	55 ft. inland
T2	1.08	.400	.228	1.15	−.31	25 ft. inland
T3	.580	.319	.215	.70	−.14	shoreline
T4	.930	.460	.240	.95	−.03	25 ft. seaward
T5	.560	.280	.138	1.00	.02	55 ft. seaward
T6	.500	.277	.175	.77	−.08	80 ft. seaward
T7	.860	.328	.166	1.17	−.20	105 ft. seaward
T8	.640	.310	.198	.83	−.20	130 ft. seaward
T9	.600	.285	.166	.84	−.14	160 ft. seaward
T10	.640	.325	.200	.84	−.135	185 ft. seaward
T11	.670	.287	.165	.61	−.20	212 ft. seaward
T12	.805	.360	.197	1.02	−.135	240 ft. seaward
T13	.675	.310	.178	.96	−.16	260 ft. seaward
T14	.740	.360	.196	.95	−.08	290 ft. seaward
T15	.710	.315	.185	.97	−.20	320 ft. seaward
T16	.590	.270	.168	.92	−.22	345 ft. seaward
T17	.780	.326	.167	1.16	−.14	370 ft. seaward
T18	.480	.247	.165	.75	−.18	400 ft. seaward
S2	7.600	4.400	1.980	.95	.19	coral soil-cliff edge
S3	9.000	4.450	1.850	1.15	.14	105 ft. inland
S4	.970	.490	.235	1.03	.04	90 ft. inland
S5	.910	.423	.206	1.09	−.02	65 ft. inland
S6	.800	.340	.185	1.07	−.01	40 ft. inland
S7	.820	.395	.204	1.01	−.04	10 ft. inland
S9	.610	.290	.198	.82	−.26	shoreline
S10	.178	.130	.075	.68	.175	25 ft. seaward
S11	.550	.270	.169	.85	−.22	55 ft. seaward
S12	.540	.270	.164	.85	−.22	80 ft. seaward
S13	.830	.433	.223	.92	−.01	105 ft. seaward
S14	.600	.300	.270	.60	−.42	130 ft. seaward
S15	.768	.395	.210	.92	−.015	160 ft. seaward
S16	.645	.330	.188	.90	−.07	185 ft. seaward
S17	.575	.290	.180	.85	−.14	210 ft. seaward
S18	.760	.310	.200	.98	−.33	240 ft. seaward
A1	1.300	.680	.450	.78	−.16	75 ft. inland base of cliff
A2	.738	.404	.243	.80	−.06	50 ft. inland
A3	.930	.540	.323	.73	−.01	25 ft. inland
A4	.630	.395	.283	.58	−.02	shoreline
A5	.846	.455	.275	.85	−.08	25 ft. seaward
A6	4.100	1.30	.650	1.30	−.33	55 ft. seaward
A7	.935	.40	.187	1.13	−.05	80 ft. seaward
A8	2.550	.73	.375	1.40	−.42	105 ft. seaward
A9	7.700	1.65	.590	1.85	−.37	130 ft. seaward
A10	10.020	7.20	3.650	.72	.25	160 ft. seaward

consist of grains of calcite coated with carbonaceous matter. Commonly the organic material also acts as a cement in attaching several carbonate grains together. Some samples contain very little carbonaceous material and are light colored, whereas others collected nearby are rich in organic matter and consequently are rather dark in color. Distribution of the organic matter is not uniform and bears no relation to position of the sample in the lagoon or the depth of water. Neither is there any relationship between the abundance of faecal pellets and organic matter.

The most striking character of the lagoon sediments is the general absence of igneous rock or mineral fragments other than calcite. Particularly surprising is this fact in view of the position of the beach sands against wave-cut basalt cliffs, yet in none of the samples were more than a very few grains of igneous material observed. Such a noteworthy absence of sediment other than that derived from the reef seems to be characteristic of other coral areas. Vaughan (1918) states that at Murray Island the beach contains much basaltic material but 200 feet seaward from the shore the total silica, iron and alumina content is only .63 per cent of the sediment. The great preponderance of carbonate material in the sediments must be due to the extremely rapid growth and erosion of the fringing and barrier reefs. At Raiatea the energy of wave action is employed not only to break up the reef but to drive the comminuted material shoreward at a very rapid rate. Hence wave action against the cliffs of igneous rock cannot supply much volcanic material before a wide beach of, coral sand is built which protects the cliff from further wave attack. Furthermore the growth of the barrier reef successfully impedes wave action so that the lagoon waters remain quiet and waves cannot sweep up the full width of the beach.

SIZE DISTRIBUTION

The near-shore, shallow-water lagoon sediments are rather uniform in their size distribution (table 1). Fine material of clay and silt dimensions is almost entirely absent from all samples and, except for an occasional pebble of coral or shell fragment, the grain size ranges from granule to very fine sand. Most of the grains of granule size are fragments of, or entire, small pelecypod shells, whereas the sands consist predominantly of comminuted coral. Irregular variation in the median diameter grain size is noted and no relationship appears to exist between the size of the median diameter of the samples and their distance from shore. The median diameter of the sub-aqueous samples ranges from .130 to 7.20 mm., the arithmetic mean is .591 mm. (coarse sand size) and the most commonly occurring median ranges from .2 to .4 millimeters. The general uniformity in size of the median of most of the samples, irrespective of their location, is believed to be the result of rather similar wave and current conditions existent over the localities sampled, in which the depth of water was found to be very shallow (2–8 ft.).

The beach material near the strand line is much like that of the sub-aqueous sediment, but at the edge of the cliffs the sediment has been considerably weathered and re-cemented into calcareous soil fragments. The weathered beach material likewise shows a greater range of size distribution and contains more silt, clay, and coarse particles of cemented silt and sand than the lagoon sediments. The extremes of the median diameters of the beach sands are .290 mm. and 4.45 mm., the arithmetic mean is 1.04 mm., and the most common median ranges from .4 to .5 millimeters. The increase in grain diameter of the sands of the beach is due chiefly to the removal of fine material by the wind. Re-cementation of grains by calcium carbonate due to weathering of part of the beach also effectively increases the coarseness of the beach sand.

Sorting of material in the various lagoon samples varies little between individuals as indicated by the phi-deviation (QDΦ)[1] which ranges from .58 to 3.15

[1] The phi-deviation equals one-half the spread in Wentworth units between the first and third quartiles.

and averages 1.01. Thus the average spread between the first and the third quartiles of the samples is 2.0 Wentworth units. Since the average median diameter lies in the coarse sand size, 50 per cent of the average lagoon sample consists of material ranging from very coarse to medium sand-grain size. The fourth quartile in all the samples contains material dominantly of fine sand size, the amount of silt rarely exceeding 5 per cent. Material of clay dimensions is absent except in one sample (S10) taken only 25 feet seaward from the strand. Absence of fine material in the near shore-waters is somewhat surprising in view of the absence of rough water and the fact that several streams emptying into the lagoon drain uplands covered with *terra rosa*. Fine-grained debris from the upland must be caught and held by the heavy vegetation and released to the streams in very small quantities. Such clay as may be carried to the lagoon is largely not deposited because the water is so shallow that even slight wave and tidal current action keeps it in suspension until it is carried out beyond the barrier reef. The small quantity of clay deposited within the lagoon is negligible, in contrast to the large quantity of coarse reef debris, and so is not observed in individual samples. Sediments constituting the sub-aerial part of the beach show characteristics similar to the lagoon deposits. The phi-deviation ranges from .73 to 1.15 and averages .96. Thus one-half of the sub-aerial beach material consists of grains ranging from granules to coarse sand. Influence of the wind in removal of the fine sediment is reflected in the slightly lower phi-deviation as compared to the sub-aqueous samples.

The size frequency curves of the lagoon and the beach sediments are almost identical in character. Nearly all the curves are skewed slightly in a negative phi-direction indicating that the mean of the first and third quartiles is a size which is more coarse-grained than the median.[2] The extremes of the phi-quartile skewness are $-.42$ and .190, and $-.162$ is the arithmetic mean. Samples taken at the strand line generally are better sorted than those taken from other positions in the lagoon, the phi-deviation and the phi-quartile skewness of the former being less.

[2] A phi-quartile skewness of one indicates an interval of one Wentworth unit between the mean of the quartiles and the median.

COMPARISON WITH OTHER CORAL LAGOON DEPOSITS

The sediments of the shoreward portion of the lagoon bordering Raiatea have certain characteristics which make them similar to coral lagoon deposits formed elsewhere. A number of samples of sediments deposited in such an environment in various widely separated localities have size frequency curves which are similar in the interval between the first and third quartiles, although the sediments may differ appreciably in median diameter (table 2). Such is particularly true of samples from the reef lagoons of the Pacific. Size frequency curves of sediments from the coral reef areas in the Atlantic show little similarity with each other or with those of the Pacific. The majority of the sediments from the Pacific coral reef islands are more coarse-grained and in general, except those from Bermuda and Andros Island, are better sorted than those from the Atlantic. This may be due to the presence of considerable quantities of terrestrial material which are deposited with the coral sands of the Atlantic except in the two localities mentioned above. Usually the average size frequency curve is skewed in a negative phi-direction, indicating the absence of much fine-grained material, but there are others, notably those of the Bermudas, Batabano, and Murray Island, in which the curves are skewed in a positive phi-direction. Bramlette (1926) states that the calcareous sands from the reef flats of Pago-Pago show a marked similarity to those of Murray Island, Australia. In both cases the sands are poorly sorted and fine material is absent which is explained by Bramlette as having been removed by strong currents in the shallow water.

TABLE 2. *Statistical comparison of coral lagoon deposits*

Authority	Location	Number of Samples	Average *Md* mm.	Average *QDφ*	Average *Skq φ*
Todd (1939).....	Bermuda.....	Average of 15	.54	.660	.16
Trask (1932).....	Florida Bays.....	Average of 8	.040	2.16	−.15
Trask (1932).....	Batabano, Cuba.....	Average of 3	.019	1.91	.14
Trask (1932).....	Bahamas.....	Average of 1	.006	2.29	−.02
Vaughan (1918)..	Bahamas.....	Average of 4	.092	2.74	−.58
Vaughan (1918)..	Andros Island.....	Average of 4	.22	.52	−.104
Vaughan (1918)..	Murray I., Australia.....	Average of 5	.79	.50	.168
Thorp (1936).....	Hermes and Pearl Reef, Hawaii	Average of 18	2.09	1.18	−.138
Bramlette (1926).	Pago-Pago Harbor, Samoa....	Average of 4	.031	1.51	−.129
Bramlette (1926).	Aua shoreline, Pago-Pago.....	Average of 9	1.08	1.10	−.155
Stark-Dapples....	Raiatea.....	Average of 48	.591	1.01	−.162
Trask (1932).....	Great Barrier Reef, Australia..	Average of 1	.055	2.29	.82

CONCLUSIONS

Near shore coral lagoon sediments of several islands in the Pacific are coarse to medium-grained sands which contain little admixed fine material. In lagoons where the water is shallow particles of silt and clay dimensions are carried into the deeper waters beyond the boundaries of the barrier reef. Lithification of such coarse-grained sands probably results in the coarsely crystalline limestones observed along the borders of ancient coral reefs. Wherever coral sediments are being deposited the percentage of terrestrial material also being deposited is so small that its presence can scarcely be recognized. This is true even at a shoreline adjacent to cliffs of volcanic rock. Such a condition is significant since it indicates that the accumulation of calcareous sands derived from coral reefs is extremely rapid, and that deposits of limestone may therefore, accumulate in certain areas at rates which exceed those of certain sandstone and shale deposits.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 1, PP. 28–31, FIGS. A–J, TABLES 1–2, APRIL, 1941

A DIAPHRAGM METHOD FOR GRAIN SIZE ANALYSIS

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ABSTRACT

The measurement of grain size in terms of the nominal sectional diameter is being used more and more in sedimentary petrography. Most methods of measurement contain significant errors and are time consuming. The use of a large diaphragm in estimating the diameter of a circle, whose area is equal to the area of the grain, greatly shortens the time. The errors involved have been found to be small enough to be ignored. The apparatus is described and parallel measurements are compared which lead to the conclusion that such a device is valuable in securing accurate grain size data in a very short time.

INTRODUCTION

Screens are commonly used to obtain sizes of particles in sedimentary petrography. There are, however, several errors involved. Shaking permits elongated grains to pass through screens, whereas rounded grains of equal volumes are retained. Mechanically disintegrated consolidated rocks may have grain enlargement destroyed, and the true size of the individual grains is not available. Individual grains in sedimentary rocks in thin sections cannot be screened, but the sizes of the grains as random cross-sections can be measured.

Wadell (1935) has shown that the diameter of a circle whose area is equal to the area of the grain, is a much better measure of true size than any other. Averages of axes, perimeters, and so forth contain some reflection of the shape. What is needed is a method of obtaining, accurately and rapidly, the grain size for frequency-distribution curves, histograms or cumulative curves.

One of the common methods is to project the image of the grain either by a camera lucida or a microprojector and to draw the outline. The surface area of the grain is then measured on the outline by a polar planimeter. The area so obtained is then calculated by a slide rule, or graphically, to the value of the diameter, in millimeters, of a circle, the area of which is equal to the area of the unmagnified grain. There are two precautions to be taken. First, the grain should not occupy more than one-quarter of the microscopic field in which it is seen, especially if a camera lucida is used. Second, the projected grain should be in the center of the field of the camera lucida, due to distortion of both the shape and size at the margins. The magnification should be such that the size of the projected image is about 70 mm. over-all.

But, the method is a great time consumer. It is practically out of the question if a thorough investigation of a large suite of specimens is undertaken, unless there is a staff of assistants available who are able to do this routine work.

In searching for a more rapid method, it occurred to me that if a circle of the proper diameter should be projected on the image of the grain so that the portions of the grain image outside the circle equalled the areas within the circle not occupied by the grain, it would approximate the nominal sectional diameter. The diameter of the circle is what is required. Better still, a variable circle, made to increase and decrease in size to correspond to the grain image would be ideal. Such an ideal would be a diaphragm mounted on the camera lucida drawing table, the opening of which could be lighted by a (colored) light from below. I have tried such an apparatus and find that it gives satisfactory results in a short time.

TABLE 1

No.	Size by Planimeter	Size by Diaphragm	Error %	No.	Size by Planimeter	Size by Diaphragm	Error %
1	.0281	.0275	− 2.2	26	.0580	.0586	1.0
2	.02875	.0290	1.0	27	.0582	.0610	4.5
3	.0294	.0280	− 4.8	28	.0589	.0563	−4.5
4	.0291	.0260	−10.5	29	.0599	.0582	−3.8
5	.03025	.0303	0.2	30	.0613	.0617	0.5
6	.0354	.0351	− 0.8	31	.0615	.0566	−7.7
7	.0389	.0380	− 2.2	32	.0635	.0672	5.5
8	.0392	.0396	1.0	33	.0637	.0665	4.2
9	.0402	.0419	4.0	34	.0642	.0662	3.2
10	.0414	.0425	2.5	35	.0672	.0664	−1.2
11	.0435	.0405	− 7.2	36	.0679	.0728	6.6
12	.0435	.0443	1.8	37	.0682	.0678	−0.7
13	.0478	.0505	5.2	38	.0688	.0695	1.0
14	.0481	.0467	− 2.9	39	.0690	.0715	3.5
15	.0497	.0510	0.5	40	.0705	.0706	0.2
16	.0506	.0520	2.7	41	.0729	.0780	6.5
17	.0514	.0572	10.0	42	.0729	.0744	1.9
18	.0516	.0450	−12.8	43	.0753	.0773	2.9
19	.0519	.0538	3.5	44	.0774	.0792	2.2
20	.0537	.0540	0.5	45	.0777	.0780	1.9
21	.0541	.0530	− 2.0	46	.0800	.0800	0.0
22	.0547	.0538	− 1.6	47	.0869	.0877	0.7
23	.0547	.0540	− 1.2	48	.1070	.1080	1.0
24	.0557	.0563	1.0	49	.1075	.1054	−2.0
25	.0570	.0582	2.1	50	.1090	.1100	0.8

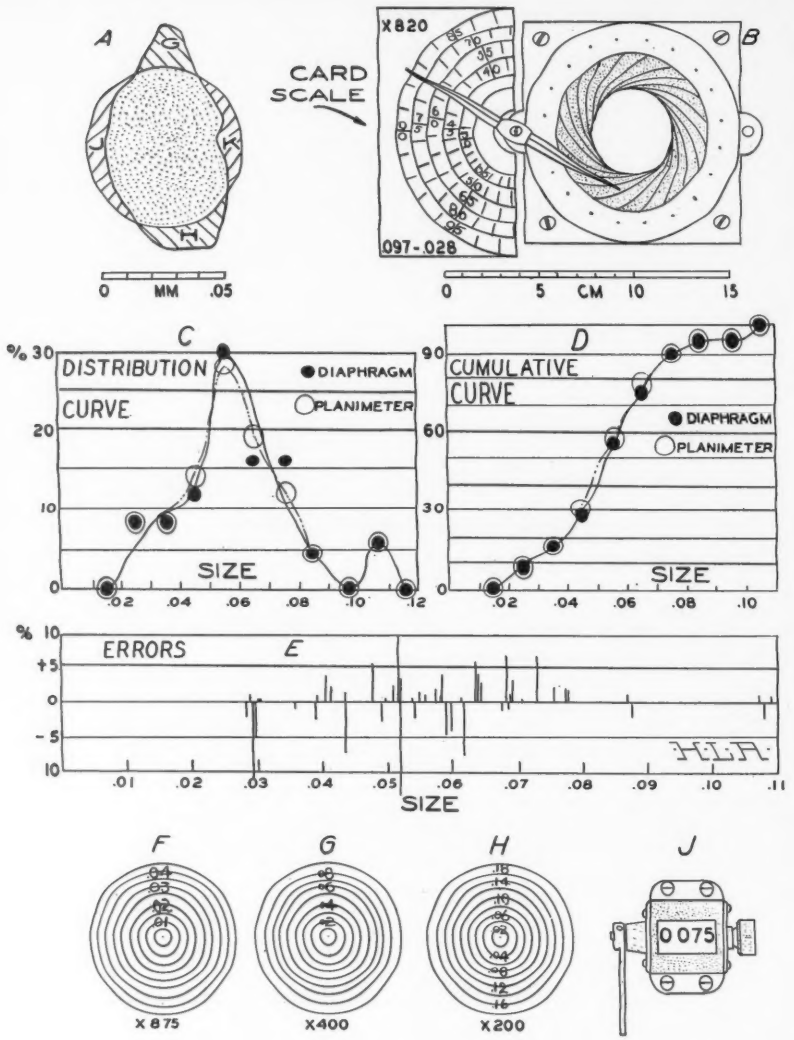
THE DIAPHRAGM

Through the cooperation of the department of physics of the University of Rochester, I obtained the use of a metal diaphragm of 80 mm. maximum opening, 20 mm. minimum aperture. This, mounted over a hole in the drawing table, permitted the light of a colored (orange) incandescent bulb to illuminate the opening of the diaphragm. The size of the diaphragm opening is controlled through a knob operating the leaves of the device through a spur gear.

The procedure is as follows: the microscopic and diaphragm lamps are turned on; the grain, to be measured, is brought by a mechanical stage into the center of the field; the diaphragm is opened or closed until the circle thus defined is the exact size to bring about an areal balance between the areas of the grain outside the circle, and the areas inside the circle not occupied by the grain. This is estimated by inspection (see fig. 1 A). Areas G+H should equal areas J+K. The diameter of the diaphragm is then measured. This is the nominal sectional diameter of the grain. The most rapid means I have used is a simple tracing paper scale, one for each objective-ocular combination, reading directly in class divisions in millimeters. This is placed just below the diaphragm and measures the diameter of the diaphragm (figs. F, G, and H). The number of grains in each class division is recorded on a set of Veeder-Root counters (fig. J). The figures so obtained are calculated into percentages and plotted. The time for measuring about a hundred grains, translating into percentages and plotting in pencil, is about a quarter hour's work.

ACCURACY

The ability to judge whether the circular area formed by the diaphragm opening is equivalent to the area of the grain is, of course, the essential element in the method. The following table is the record of 50 quartz grains in a thin section (of



FIGS. A.—The grain is indicated by the dotted area plus areas lettered *G* and *H*. The circle represents the opening of the diaphragm. To secure the nominal sectional diameter of the grain, the diaphragm (the circle) is adjusted in size so the areas *G* plus *H* equal *J* plus *K*. This is obtained by inspection.

B.—Shows the diaphragm with double pointed arrow attached to operating knob. The arrow sweeps across the card scale reading directly in grain size in millimeters for an objective-

Medina sandstone from the Rochester gorge) measured by this method and the planimeter method.

These data can perhaps be evaluated by noting how close the two curves check in figure 1 C and D. The involved errors are shown in figure 1 E.

Table 2 gives the value of the mode from the distribution curve, and the median and quartiles from the cumulative curve for the two methods.

With comparatively little practice the diaphragm method gives very satisfactory results in a relatively short time. I can recommend it to others who are interested in grain-size measurements.

TABLE 2

	Diaphragm	Planimeter
Mode	.0550	.0550
First quartile	.0425	.0410
Median	.0525	.0520
Third quartile	.0650	.0640

REFERENCE

WADELL, HAKON, *1935*, Volume, shape and roundness of quartz particles: *Jour. Geology*, vol. XLIII, p. 263.

ocular combination magnifying 820 times. Other types of scales are shown in figures F, G, and H.

C.—Plot of the distribution curve of 50 grains of quartz in a thin section of Medina sandstone from the Rochester Gorge. Solid line: By diaphragm method. Dash-dot-dot line: by planimeter-calculation method.

D.—The same data plotted as a cumulative curve.

E.—The errors involved in the rapid diaphragm method, using the slow planimeter-calculation method as standard. The positive and negative errors are in fair balance.

F.—Tracing paper scale for diaphragm ×875.

G.—Tracing paper scale for diaphragm ×400.

H.—Tracing paper scale for diaphragm ×200.

J.—Veeder-Root counter for recording of grains of a given size. A set of 12 counters was used.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 1, PP. 32–36, TABLE 1, APRIL, 1941

THE STABILITY OF MINERALS IN SANDSTONE*

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ABSTRACT

Some published data indicate that several minerals, some of which are usually considered relatively stable species, become corroded within fresh and unweathered sandstone strata. This solution or decomposition is evidently due to the action of solutions within the buried strata, and the surficial alteration due to weathering is not included in this discussion. This corrosion of minerals has suggested that some of the less stable ones may have completely disappeared from ancient strata. Examples are presented which show that hornblende and epidote have disappeared from some Miocene sandstones. The mere absence of some relatively unstable mineral, especially some of the ferro-magnesian group, therefore seems doubtful evidence for conclusions regarding the source rocks or the stratigraphic relations of sandstones. These considerations seem especially important for older formations, as the small assemblage of stable minerals, that is usual in early Paleozoic strata, may represent only a survival of the fittest.

The chemical stability of minerals in the source rocks of sediments under the influence of weathering and their physical stability during transportation of the sediments have received considerable attention, and are generally recognized factors influencing the mineral content of sedimentary rocks. Several papers have described a corrosion of detrital mineral grains which was effected within the sandstones, and is not related to surface weathering. Boswell (1933) has reviewed and discussed most of the papers bearing on this stability of detrital mineral grains. As pointed out by him, Thoulet was one of the first writers to consider this subject and to note that the complexity of mineral assemblages in sediments increased upward in the geologic column in consequence of the relatively unstable nature of some minerals such as pyroxene and olivine. Among others, Edelman and Doeglas (1934) have presented evidence of a "diagenetic" corrosion of detrital grains of staurolite, kyanite, garnet, epidote, and titanite, and mentioned their previous paper on similar data for two of the less stable minerals, pyroxene and amphibole. The described examples of solution or corrosion of mineral grains within sandstones do not include much evidence of alteration or conversion to other minerals within the strata, except for some of the titanium minerals. Most of the evidence of changes in the titanium minerals is indirectly inferred only from the common occurrence of authigenic titanium minerals, as is evident from the reviews by Boswell. Evidence that the authigenic anatase was formed from titanite in one occurrence was mentioned by the writer (1934).

The corrosion of certain minerals has suggested that some of these minerals may have disappeared entirely from some ancient strata, but evidence on this inference is ordinarily not apparent. Examples are presented here which show that two of the relatively unstable minerals, hornblende and epidote, have disappeard from some Miocene sandstones of California. These examples indicate a method of securing additional data on this subject.

The examination of calcareous concretions within clastic sedimentary rocks indicates that many of them are formed within the strata, but at an early period before much of the compaction and lithifaction; this may thus be considered a typically diagenetic process. This is especially well shown by the concretions in the Monterey formation of California,

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examined by the writer. The thin rhythmic bedding extends uninterruptedly through the concretions, though the individual beds are thicker within the concretions, and include preserved diatoms, volcanic glass shards, and other relatively unstable constituents that either are not preserved or are partially altered in the same beds outside the concretions.

Samples from two large calcite-cemented sandy concretions and from the equivalent sand immediately adjacent to the sampled parts of the concretions were collected from the Hambre sandstone (Miocene) in the area south of San Pablo Bay, California. The marked difference in their content of hornblende is indicated in table 1 (first four samples).

The percentages of light minerals (lighter than bromoform) are only approximate determinations, as accurate distinction of the proportions of quartz and alkalic feldspar requires an undue amount of work for the value it may have. The percentages of andesine and volcanic glass shards were more quickly and accurately determined in the refractive index liquids. The only striking difference in the light fractions is that the shards of volcanic glass are quite isotropic and apparently unaltered (index 1.51) in samples from the two concretions, but are much altered in the adjacent sandstone samples and consist of a weakly birefringent aggregate, which shows a mean index near 1.49, and is apparently in major part a zeolite. The hornblende that constitutes nearly half of the heavy mineral fraction in the two samples from the concretions is nearly lacking in the adjacent sandstone samples (the basaltic hornblende entirely lacking), and the total heavy mineral percentages show a corresponding decrease. Other minerals are not significantly different in the four samples, except for the relative increase in their percentages in the samples lacking much hornblende. The absolute quantities of these other minerals is not significantly different, as is evident from a comparison of their percentages with the proportion of total heavy minerals in the four samples.

The evidence of the loss of hornblende from this sandstone suggested some doubt regarding certain interpretations made in a recent heavy mineral study by Cogen (1936). He presented heavy mineral data on some Miocene sandstones on the north side of the Santa Monica Mountains in Los Angeles County. The mineral zones cut across stratigraphic units in such abrupt manner that one of the sandstones characterized by a dominance of hornblende and epidote showed showed these minerals absent in less than one-half mile to the east. Thus the same sandstone unit was included in his mineral zone C at one locality and in his mineral zone B in the locality less than one-half mile distant. Cogen states, "Zone C is distinguished by the presence of hornblende and epidote and the relative proportions of ilmenite, titanite, and garnet. Heavy minerals are comparatively abundant here. Hornblende and epidote are absent from zone B but it possesses the same ilmenite-titanite-garnet proportions characteristic of the underlying zone C. The heavy mineral content of the sediment is small."

A few large concretionary bodies of calcite-cemented sand are present in this sandstone, though they appear to be less dense and impervious than those in the finer-grained Hambre sandstone. Samples were collected from two of these concretionary masses and from the immediately adjacent sandstone from the outcrop of Cogen's samples 13B and 14B. Mineral data on my samples from this locality are shown in the last four samples of table 1. Even the samples from outside the concretions show percentages of certain minerals that differ considerably from Cogen's data, but this is evidently due in large part to the use of different size fractions of the sands in the two studies. The writer used a fraction of smaller maximum size and of a larger range in size than the fraction of $\frac{1}{4}$ to $\frac{1}{8}$ mm. that was used by Cogen. Thus, the much larger percentage of zircon shown here is due to the fact that most of the

TABLE 1. *Percentages of mineral grains in samples of sandstone and in adjacent calcareous concretions*

	Appx. percentages of the light mineral fraction							Percentages of the heavy mineral fraction													
	Quartz	Alkalic feldspar	Andesine	"Aphanitic"	Volc. glass shards	Altered Volc. glass	Percentage of heavy minerals	"Leucoxene"	Black opaque	Chromite	Zircon	Garnet	Tourmaline	Rutile	Titanite	Glaucophane	Andalusite	Epidote and zoisite	Actinolite	Brown hornblende	Green hornblende
San Pablo Bay Area																					
Hambre sandstone, Sample no. 1.....	20	20	35	15		10	1.1	2	19	4	12	3	1	½	10	1	½	37	5		5
Sand from concretion adj. to Sample no. 1.	20	15	30	20	15		2.0	2	13	3	5	3	R	R	6	1	R	17	6	6	38
Hambre sandstone, Sample no. 2.....	15	15	40	15		15	0.7	5	16	5	9	5	2	½	12	2	1	33	5		4
Sand from concretion adj. to Sample no. 2.	20	15	35	20	10		2.2	2	10	3	4	2	2		5	½	1	20	4	5	41
Santa Monica Mountains Area																					
Modelo sandstone, Sample no. 3.....	20	25	40	15			1.0	25	15		20	15	½	½	22			2			
Sand from concretion adj. to Sample no. 3.	20	30	40	10			2.5	5	15		12	5	R		10			53			R
Modelo sandstone, Sample no. 4.....	25	30	35	10			0.8	28	12		18	10	1	½	30						
Sand from concretion adj. to Sample no. 4.	30	25	30	15			1.1	20	17		20	10	½	R	27			6			R

Micas not included, but are abundant in the samples of Modelo sandstone. R = rare = 1 grain several hundred.

zircon crystals are smaller than ⅛ mm., and were, therefore, not included in the more coarse-grained fraction used by Cogen. The "leucoxene" shown in my tabulation includes opaque grains that are coated with leucoxene and also those with a more rusty coating. A more strenuous preliminary treatment with hydrochloric acid may have removed such coating from more of the black opaque grains shown in Cogen's data. Nevertheless the mineral data for the two samples of sandstone are rather similar to those of Cogen from the same locality, which were included in his mineral zone B. However, the mineralogy of the sand within the concretion of sample no. 3 at this same locality contains much epidote and is thus more similar to his mineral zone C.

The disappearance of the epidote from the sandstone and its preservation within the calcified body of concretionary sandstone seems evident. Possibly hornblende was originally more abundant as the rare grains of hornblende present in the concretion are long and delicate "skeletal" forms with cockscomb terminations that suggest corrosion within the strata, as they could have survived very little transportation and are present only in the concretion. Because of the massive character of the sandstone at this locality, there is no evidence that the concretions were formed before much of the compaction of the sediments. Therefore, some mineral alteration may have occurred before these concretions were formed. However, in the concretion sample no. 4, it seems possible that some epidote has been lost from within the concretion as well as from the adjacent sand. It was particularly apparent that this concretion was not as dense and impermeable as other concretions, and the abundant biotite was nearly as much altered in the concretion as in the adjacent sand, though the biotite was black and little altered in the nearby concretion of sample no. 3. Also the table shows that this concretion has a higher percentage of "leucoxene," including the rusty coated opaque grains, than does the other concretion. In fact,

even the rusty stain of the weathered surface zone had permeated somewhat into this concretionary sample (no. 4), and this may account for most of the change in the biotite and opaque grains.

The loss of hornblende and epidote that has been described, and many of the occurrences of corroded detrital grains are evidently not the result of weathering processes. Some of these samples came from beneath the surficial zone of a few to 20 or more feet of rusty weathered sandstone, which is obvious in the deep roadcut exposures; the sandstones containing hornblende and epidote (Cogen's zone C) show no appreciable differences in these minerals above and below this surficial zone of greater weathering. The corrosion of more stable mineral grains, such as staurolite and garnet is recognized in core samples from deeply buried strata as well as in the outcrop samples of these strata.

Many additional data are necessary before the relative stability of detrital mineral grains, under various conditions, can be profitably considered. Composition of the solutions within the strata would seem to be one of the important factors, as some sandstones of Eocene and Cretaceous age in California contain minerals such as hornblende and epidote, though these minerals have disappeared in some of the Miocene sandstones described here. It is perhaps significant that apatite, which is so easily attacked by weakly acid solutions, is common in the sandstone samples which have lost hornblende and epidote. This apatite is not shown in the table because the samples were treated with dilute hydrochloric acid, but examination of part of the original samples showed that apatite is one of the most abundant heavy minerals.

This evidence seems to indicate that the mere absence of some relatively unstable minerals cannot be safely used as a basis for interpretations regarding the stratigraphic relations or the source rocks of sandstones. From the evidence of the corrosion of some relatively stable minerals, even garnet under some conditions, it would seem that due consideration should be given the possibility of their complete disappearance in some of the oldest strata. The relatively small assemblages of heavy minerals in many of the early Paleozoic formations, and especially the fact that these small assemblages commonly include only the relatively stable minerals, (zircon, tourmaline, rutile, black opaques, and garnet), suggests that a loss of less stable minerals from within the strata may be the explanation. The presence of some of the less stable minerals in some of these older strata does not necessarily vitiate the general relationship suggested, as factors such as permeability and composition of the solutions would doubtless prevent any great regularity of a relationship showing progressive modification of these minerals in the geologic column. However, the presence of small amounts of one of the less stable minerals, such as pyroxene in early Paleozoic strata, suggests the desirability of careful checking to see that this is not a result of contamination or inclusion of the mineral within larger grains that may have been crushed in the laboratory treatment.

The well-established results of some heavy mineral studies of sediments for interpretations regarding their stratigraphic relations show that the conclusions suggested in this paper do not discredit the value of heavy mineral studies of sediments. However, it seems to emphasize the importance of another one of the many factors that must be considered in any interpretation. The mere absence of certain minerals in ancient sandstones, particularly of the relatively unstable minerals, seems of doubtful significance, and if additional data show that the small suite of relatively stable minerals in the oldest sedimentary strata is largely due to the stability relations of the minerals, it is evident that conclusions regarding the source rocks of these sediments are difficult and of questionable value except as interpreted from the minerals actually present, and the distinctive characteristics of these minerals.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 11, NO. 1, PP. 37–41, FIGS. 1–2, APRIL, 1941

THE CLASSIFICATION OF WAVE-FORMED RIPPLE MARKS

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ABSTRACT

Wave-formed oscillation ripple marks are described in textbooks as symmetrical in cross-section while asymmetrical ripple marks are described as always formed by current action. Observation shows that asymmetrical ripple marks having their steep sides toward the shore are very common in the shallow water along the shores of lakes having a sandy bottom. A study of the method of formation of these asymmetrical ripples shows that they are not usually produced by currents but are formed by the oscillatory movements set up on the bottom by the passing breakers. These movements are unequal in time and intensity in opposite directions. The result is asymmetrical ripple marks which usually migrate in the direction of wave travel. Therefore wave-formed ripple marks should be divided into two classes: Symmetrical oscillation ripples and asymmetrical oscillation ripples.

Water-formed ripple marks are at present classified as asymmetrical or current-formed and symmetrical or wave-formed. Nowhere in the literature of ripple marks, with one exception (Ayrton, 1910, pp. 285–310), is the possibility admitted of asymmetrical ripple marks being formed by wave action. Their origin is always ascribed to the action of currents. Johnson (1919, p. 493) in discussing the work of previous investigators makes the following statement. "The term ripple-mark is so firmly established in the literature to include both the symmetrical and asymmetrical types that it seems wisest to follow the usage, prefixing the words 'oscillation' and 'current' to make clear the necessary distinction." Again he says (Johnson, p. 507), "Thus oscillation ripples may be made slightly asymmetrical by a feeble current." Kindle who made extensive field studies and took numerous moulds of ripple marks under water always ascribes the origin of asymmetrical ripple marks to the work of currents. He says (Kindle, 1917, p. 28) in discussing Ayrton's work, "None of the numerous wave ripple mark moulds which I have taken under water show any modification of symmetry with reference to the shoreline." Bucher (1919, p. 183) says, "The profile of oscillation ripples is strictly symmetrical with sharp crests and broad round hollows." Again he says (1919, p. 185), "Oscillation ripples are stationary. They cannot advance in either direction"

Careful observations by the writer extending over a number of years shows that along the entire extent of the eastern shore of Lake Michigan as well as along the sandy shores of the numerous inland lakes of the region, asymmetrical ripple marks are very numerous. Out to a depth of 3 or 4 feet in Lake Michigan and to a depth of about 18 inches in the smaller lakes the asymmetrical type is much more common than the symmetrical. In fact it is safe to say that asymmetrical ripples are always present beneath the water on a sandy beach with a breeze onshore strong enough to form small breakers.

From the hundreds of observations made only a few examples can be given. At Duck Lake near Whitehall, Michigan, on June 13, 1938 asymmetrical ripple marks were observed 6 feet from shore in water about a foot deep. They were 8½ inches from crest to crest. The long slope was 6½ inches wide and the short slope 2 inches. The short slope faced the shore and the ripples were traveling towards the shore at the rate of 8½ inches in 20 minutes. The waves were about 10 inches high and 20 feet long and were coming directly onshore. The bottom was covered with asymmetrical ripple marks for a distance of 100 feet offshore where the depth

was about 3 feet. The bottom slope was gradual and the distance between the crests of the ripples became less as the depth of water increased. In approximately the same place on August 1, 1938, waves 8 inches high came onshore at an angle of about 45 degrees. From the shoreline out to a depth of 12 to 15 inches these ripple merks were asymmetrical and 6 to 7 inches wide. As the distance from shore increased and the water gradually deepened the ripple marks became smaller and less symmetrical until in 26 inches of water they were nearly symmetrical and 4 inches wide. These ripples were all moving slowly shoreward.

On the next day near Old Channel, north of the White Lake piers, waves estimated to be 2 feet high were breaking over the first "ball," or permanent ridge, which was here about 150 feet offshore. After crossing the ball the breakers reformed inside it into pure oscillation waves. These in turn broke on a temporary sand ridge that was present on the lake bottom about 25 to 30 feet offshore. On the top of this ridge the water was 5 inches deep and in the trough between the ridge and the shore it was 16 inches deep. On the outside of the ridge in water 1 to 3 feet deep asymmetrical ripples 6 to 8 inches wide moved slowly up the slope toward the shore. The top of the ridge was swept clean by the currents across it. On the inner side of the ridge ripples 6 to 8 inches wide were moving down the slope toward the shore and were becoming smaller with increasing depth.

This ridge extended several hundred feet along the shore and was attached to the shore at both ends. In one place where the crest of the ridge was slightly lower than elsewhere, submerged floats showed that a gentle outward current was moving over it. Here asymmetrical ripples were present having their short slopes toward the shore but they were stationary. The form of the ripples was being determined by the oscillatory movements caused by the waves but enough sand was being moved outward by the bottom current to prevent their travel in the direction of wave movement. In a few cases asymmetrical ripples with their steep slopes toward shore have been seen to move slowly offshore. This was observed by the writer at Little Point Sable in 1923 and again at Duck Lake Beach in 1937.

A striking example of the control of the shape of asymmetrical ripples by the unequal oscillating movements of the water by the breakers was seen at the outlet of Duck Lake on July 10, 1940. The stream flows a few hundred feet over the beach sands before entering Lake Michigan. On that date the conditions were such that an outward sloping sand mass was being deposited in the edge of the lake by the stream and at the same time breakers about 6 or 8 inches high were moving almost directly onshore. The surge of the swells in Lake Michigan was such that sometimes the flow of the water from the stream was held back for a short time, followed by a period of rather rapid outward currents. Thus there was frequently a definite outflow of water from the stream but with the breakers moving onshore through it. At such times asymmetrical ripple marks formed on the bottom with their steep sides toward the shore but at the same time the sand and small debris on the bottom showed a definite offshore movement over the bottom although this movement was made somewhat irregular by the impulses caused by the moving breakers. These were not the "anti-dunes" which sometimes migrate upstream in a swift current but were true asymmetrical oscillation ripples produced by the breakers. Occasionally the outflowing stream current was strong enough to overcome the energy of the waves temporarily and the bottom was swept smooth, and a few times stream current ripples with their steep sides facing offshore began to cover the bottom. Again as the current slackened the unequal oscillating movements of the breakers gained the ascendency and the bottom again became covered with the asymmetrical oscillation ripples with their steep short slope facing the shore. These latter ripples were probably migrating off-

shore but the period of their maintenance was so short that a determination of this point was impossible.

Considering the extensive occurrence of asymmetrical oscillation ripple marks it seems strange that previous investigators have generally failed to observe their presence. The only mention is by Ayrton (1919, pp. 285–310). She states that they are the most common type of ripple mark on the English coast where

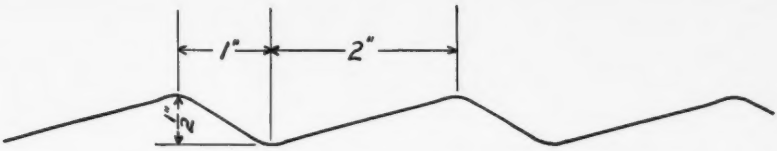

FIG. 1.—A cross-section of asymmetrical ripples in Silver Lake.

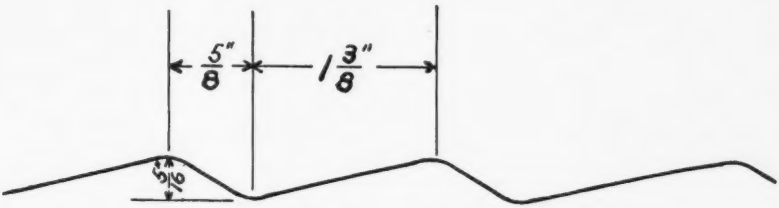

FIG. 2.—Cross-section of asymmetrical ripples in White Lake.

she did her work. Although some of Kindle's work was done along the north shore of Lake Erie he says (1917, p. 12), "Asymmetrical ripple-mark is seldom met with in lacustrine deposits," and goes so far as to suggest that the absence of asymmetrical mark may be taken as a proof that the deposits are lake formed rather than ocean formed and gives as a reason that it is only in the ocean that currents exist sufficient to cause ripple marks to be asymmetrical.

It is true, as Kindle says, that the determination of the true shape of a ripple mark under water is attended with some difficulty but in the clear water such as is common in the Michigan lakes it is possible to check the observations repeatedly with both the eye and the hand, and to make direct measurement on the bottom even when the waves have some considerable size. When making such observations I have many times asked bystanders to check my observations with respect to symmetry of ripple marks and have always found their observations to agree with my own. Following the practice of Kindle (1917, pp. 6–8), I have also taken several moulds of ripple marks. The dimensions of two of these of the asymmetrical oscillation type are shown in figures 1 and 2.

Figure 1 shows a cross-section of a series of ripple marks in the edge of Silver Lake near Little Point Sable, Michigan. The beach is of clean sand much like the dune sands of nearby Lake Michigan. The mould was taken in 6 inches of water, 5 feet from the waterline. The waves, which were breaking occasionally, averaged 3 inches high and about 6 feet long. The ripples were migrating slowly towards the shore. Sunken floats indicated unequal reciprocating water movements on the bottom but no current either toward or away from shore. Figure 2 is a cross-section of ripples taken near the end of Lyons Dock in White Lake near Whitehall, Michigan. The dock is built of old

timbers which have been covered with sand dredged from the adjoining lake bottom. The dock lies northwest-southeast and storm waves have made a shallow break about 50 feet wide in it. The southwest winds cause waves to pass through this opening and these cause the formation of ripples on the sandy bottom. On both sides of the break is open lake. Submerged floats showed no definite current through the opening but did show unequal oscillating movements of the bottom water. The mold was taken in water 5 inches deep with the waves 2 inches high and 5 feet between crests. The ripples were migrating slowly in the direction of wave movement and the sand traveling with them was being added to that already deposited along the leeward side of the break.

It seems very clear that the term "current" as used by previous investigators of ripple marks means a steady current flowing in one direction and not an oscillating movement greater in one direction than the other. For example, Johnson (1919, p. 507) says, "Oscillation ripples may be made slightly asymmetrical by a feeble current." Kindle (1917, p. 30) says, "The symmetrical crests of wave ripples are extremely sensitive to very gentle current action. A current which is barely perceptible is sufficient to modify wave-made ripple mark and give it a slightly asymmetrical form." Also Bucher (1919, 149–210) in every case he discusses, either implies or states a single direction of water movement in accounting for asymmetrical ripples.

The almost universal presence of asymmetrical ripple marks and the absence of definite shoreward currents in the breaker zones of both the small and large lakes of Michigan requires an explanation. If it is true, as most earlier investigators have held, that asymmetrical ripple marks are caused only by currents it means that with onshore winds there must be a constant current on the bottom *toward* the shore. However this is directly opposed to what is generally believed and taught regarding the general direction of bottom currents near shore under such conditions. It is stated in the majority of textbooks that as the waves approach the shore the water on the surface is moved toward shore and then moves out again as a current on the bottom called the undertow (Chamberlin & Salisbury, 1909, p. 298). According to this theory, if asymmetrical ripple marks are caused by a current over the bottom they should be numerous in the breaker zone but with their steep sides *away* from the shoreline.

With these considerations in mind careful observations were made of the bottom movements of water in places where the bottom was covered with asymmetrical ripples. In the first observations ink was used as an indicator. This was placed in the water at the desired depth by means of a medicine dropper. It was found that close to the bottom as the breaker passes over, there is an oscillatory movement of the water but that the velocity is unequal in the two opposite directions. At the time of the passage of the breaker there is a relatively strong surge towards shore. This is followed, as the wave passes, by a reversal of the direction of bottom movement which is weaker but longer continued. Since, as is well known, the friction of the water on the sand grains increases much more rapidly than does the velocity of the current (Twenhofel, 1926, p. 30), it follows that the short, quick surge towards the shore may carry a greater amount of sand than the slower, longer surge away from shore.

Ink is not entirely satisfactory as an indicator since it disperses rapidly in the water. A better indicator for observing bottom movement was found to be water-soaked bark which has a specific gravity just slightly greater than that of water and so remains on the bottom but touches it so lightly as to be moved easily backward or forward by the moving water. It was discovered that close to the bottom the total movement of the water away from or towards the shore as the waves pass is little or nothing. While small pieces of bark would frequently move over the crest of the ripple to the adjoin-

ing trough yet the movement was as often away from shore as toward it.

It was also noticed during the investigations, that small plants on the bottom were swept back and forth by the water movement. This suggested a method of observing the time of change of current direction and the time occupied in the flow. Strips of thin cotton cloth about one-eighth of an inch wide and a few inches long were embedded in the sand of the bottom so that about two inches of the strips projected. By this means it was seen that as the breaker passed there was a quick movement toward shore which was relatively strong. Then this movement was reversed and a current of longer duration and less intensity moved out toward the next approaching breaker and then the series was repeated. The transportation of sand toward shore during the short, intense onshore surge was greater then during the relatively slow offshore surge and thus the ripples became asymmetrical in form and usually travel in the direction faced by the shorter slope. Since they are occasionally observed to travel in the other direction, as in the case described at the outlet of Duck Lake, it is clear that in the case of asymmetrical wave-formed ripples, the ripple form is the result of the oscillatory movement of the water and does not depend on a constant current movement. Sometimes the quick shoreward surge is so strong that secondary ridges are momentarily formed on the shoreward slopes of the ripples and sand is sometimes thrown into suspension. This also happens in the opposite direction but to a lesser extent with the outward surge. The exact shape of ripple mark which results from these oscillatory movements which are unequal in time and intensity, depends principally on the relation between the velocity and duration of the opposing movements. If the amount of sand transported in the ripple by the quick forward movement set up by the passing breaker is greater than that moved in the opposite direction by the longer slower movement the ripple becomes asymmetrical and moves in the direction of travel of the breaker. The less the difference becomes between the transporting power of the two opposing movements the more nearly symmetrical the ripples become and the slower their forward movement. This is what occurs with any breaker of given size as the depth of the water increases. At some depth below the surface the breaker loses its asymmetry and becomes a pure wave of oscillation. When bottom currents are moving in a direction opposite to that of the breakers the forward movement of the asymmetrical oscillation ripples may be stopped, or, in rare cases even reversed, but the form of the ripple marks continues to be controlled by the passing breakers so long as the movements set up by them are dominant. However, if the outward moving bottom current becomes strong enough to take control, the wave-formed ripples disappear and a new set of true current ripples form with their slopes in the opposite direction.

Thus wave-formed ripple marks should be placed in two classes: symmetrical oscillation ripples, which do not travel, formed by waves of oscillation which act on the bottom but are not distorted, and asymmetrical oscillation ripples, which usually do travel, and which are formed by distorted oscillation waves.

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DOMINANT FACTORS IN THE FORMATION OF FIRM AND SOFT SAND BEACHES—A DISCUSSION

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Dr. E. M. Kindle has called attention to the occurrence of soft and hard sand beaches in juxtaposition, and has offered an explanation of such occurrences. (1935)

His explanation involves the following points: (1) in dry sand the interstices between the grains are filled with air which permits the grains to move freely under pressure one against another; (2) entrapment of air in the sand in the upper part of the beaches which are not covered long enough at high tides for expulsion of all the air; (3) complete expulsion of the air and a drawing together of the grains by capillary force of interstitial water in the lower parts of the beaches.

Experiments are described showing the porous structure developing from entrapment and escape of air in jars of sand. The addition of water from the top of the jars in these experiments cause a zone of "open packing" in the upper parts of the jars as contrasted with "close packing" of the sand where the water was introduced from the bottom of the container.

The facts presented by Kindle may be interpreted somewhat differently, or perhaps it would be better to say interpreted with somewhat different emphasis.

"Effervescence" or boiling of the sand has been observed in shallow water covering a sand bar at high tide. This is due to escape of air. Such an effervescence lifts the sand grains apart causing an open packed porous structure. This expulsion and entrapment of air in the upper parts of beaches, which dry out thoroughly between the tides, tends toward an open structure. Besides this factor, the upper parts of the beaches are subject to reworking by wind and moving organisms. Wind shifted materials settle into very open packing. In the lower part of the beaches, the sands are subjected to a longer "shaking" by the surf, and the sand grains settle into closer packing, not so much due to the capillary forces but by mechanical effects of wave and surf action. Since the lower beach is damp between tides, being exposed relatively short intervals as compared with the upper beach, the effects of air expulsion and disturbance by such factors by wind are small.

The well known experiments of Mead (1925) illustrate beautifully the principles involved in the formation of quicksand. Rising water through sand tends to lift the grains into an open state of packing; in fact, quicksand is simply sand kept in open packing commonly by rising waters. Kindle has pointed out that a wire nail dropped onto wet sand (saturated) does not penetrate as far as the same nail dropped from the same height onto dry sand. The state of packing of the saturated sand or of the dry sand is not given. The "binding" effect of the water which may give sand a rather surprising strength probably caused the effects noted in this experiment. It is equally true that a wire nail dropped onto dry sand in a state of open packing will penetrate much farther than when dropped from the same distance onto dry sand in a state approaching close packing.

Kindle further suggests that because steep beaches are well drained they tend to open structure. In so far as drainage tends to permit drying out between tides and thus renders them more susceptible to disturbing factors, this is probably the case. Drainage itself, however, permits granular materials to settle into closer packing, making for firmer structure.

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NOTES

GRAIN COUNTS WITH THE PETROGRAPHIC MICROSCOPE

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The following remarks are prompted by a short article which appeared recently in this Journal (W. A. White, *Jour. Sedimentary Petrology*. 10, no. 2, p. 91, 1940).

In recent years the trend in heavy mineral investigations has been towards a greater accuracy in describing the mineral composition of heavy residues. Descriptive terms such as "abundant," "rare," "scarce," etc., although still used in some types of investigation, have largely been replaced by expressing the relative abundance of each mineral as a percentage of the whole assemblage. These percentages are obtained by counting the number of grains of each particular mineral that occur in a total of 500 grains or thereabouts. Some controversy has arisen as to the accuracy of this method, but it is used now so frequently since it is felt that percentage figures explain the "make-up" of a residue much more readily that any descriptive terms, that it has probably come to stay. Naturally these percentage figures should not be interpreted as absolutely accurate, for in many residues a mineral is found, by means of counting, to make up only 0.15% of the residue, and this figure implies an accuracy far beyond that obtainable by the usual methods of collection and laboratory examination of samples.

The writer has counted over many hundreds of heavy mineral slides, and the following notes may be of assistance in the actual mechanics of counting the grains.

The writer uses a Watson Advanced "Service" petrological microscope fitted with a 1″, ½″, and ¼″ objectives. The ½″ objective is used for grain counting, for it gives a sufficiently high magnification to make the grains easily identifiable and the field is not too large. The grade sizes usually examined are the −60+115, and the −115 +250 (Tyler sieves). It has been found most advantageous to have the grains spread as evenly as possible over the slide. For example, in a series of soil residues recently examined, the grains in 12 or 13 fields were counted, each field containing 40–50 grains.

The first field counted is in the top north-east corner of the slide which is gradually worked over by proceeding more or less in straight lines down and up; a mechanical stage could be used but is not really necessary. No special grids are required as the cross-hairs divide the field into four areas. The grain counting is usually begun on the north-south line (centre line) of the north-east quadrant, and continued around to the same position in the north-west quadrant. The grains are counted in the following order: opaque grains (ilmenite, limonite, leucoxene, etc.), rutile, zircon (or the most plentiful non-opaque mineral), and the minor constituents. The counting is made easier by using reflected light for the opaque grains, convergent non-polarized light for rutile, and polarized light with the convergent lens for the remaining minerals. Such a routine saves time, and there are generally very few grains which are not readily recognizable after the preliminary examination of the slide. Certainly not much longer than 20 minutes is required for the counting, recording, and obtaining percentages of the average kind of residues obtained from sediments and soils.

It is much less tedious and tiring to count the grains in a whole field than it is

to count individual grains as they meet the cross-hairs when the slide is moved by a mechanical stage, and certainly less eye-strain is involved.

Naturally each investigator evolves his own method of work, but so far as the writer is concerned the greatest aid to this rather monotonous and tedious grain counting has been the use of a $\frac{1}{2}''$ objective, a suggestion made to me by Professor P. G. H. Boswell in London some years ago.

PENNSYLVANIA'S SCHOOL OF MINERAL INDUSTRIES

Mineral Industries, the official publication of the Pennsylvania State College in number 2 of volume 10, November, 1940, describes the program of Pennsylvania State College in its effort to develop the use of the mineral resources of the State of Pennsylvania, to train young men and women for such work and, through extension services, to disseminate information relating to mineral resources among the people of the State. Plans of the four floor of the Mineral Industries building are shown and the uses to which the floor space are put are indicated. These plans are worthy of study by those considering remodeling of old or construction of new buildings intended for instruction and research in discovery, development and utilization of mineral resources. The fields of study are stated to be Geology, Mineralogy, Geography, Mineral Economics, Meteorology, Mining, Mineral Preparation, Petroleum and Natural Gas, Metallurgy and Ceramics. The work in extension carries the influence of the School of Mineral Industries to the people of the State in general and to the teachers in the public and other schools of the State in particular.

Sedimentary petrography by Henry B. Milner, 3rd Ed. (1940). 666 pages, (601 pp. of text and illustrations; 13 pp. of lists of minerals; 24 pp. of bibliography; 28 pp. of subject and author index); 100 text figures; 52 plates, 5.5×8.5 inches, cloth. Thomas Murby and Company, 1 Fleet Lane, E. C. 4, London; Nordeman Publishing Company, Inc., 215 Fourth Avenue, New York City. Price. $10.00.

Students interested in sedimentary petrography will welcome the appearance of the 3rd edition of this standard work, which has been completely revised and expanded to include new data and technique. Much of the material taken from the second edition has been reorganized and re-written. The book consists of 15 chapters and eight appendices.

The section on laboratory technique has been expanded from three to six chapters. The new material includes the following: mechanical analysis of sediments, mineral separation by flotation, X-Ray, spectrum, fluorescence and micro-chemical methods of mineral analysis.

The diagnostic properties of about 130 sedimentary rock minerals are described and photographs or drawings of characteristic grains from various localities are given for about 60 minerals.

The chapters on the petrography of consolidated sediments, the principles and practice of differentiation and correlation of sediments, examples of differentiation and correlation of sediments by petrographic methods, the bearing of sedimentary petrography on paleogeographical problems, and the application of sedimentary petrography to the study of soils and related surficial deposits have been altered but little from the second edition.

A new chapter emphasizes the application of sedimentary petrography to building and highway construction, forensic science, medicine and problems of water supply; similarly modern applications in the asphalt, ceramic and refractories industries are discussed with a bibliography for each subject given.

The appendices include the more common sedimentary rock minerals arranged in table form according to systems of crystallization, hardness, specific gravity, intermediate indices of refraction, birefringence, and optical sign. A selected bibliography of nearly 800 items which covers the various phases of petrographic work dealt with in the text is given so that the reader may obtain supplementary information. A separate subject and author index is given. The subject index contains many cross references which facilitates the use of the book.

The subject matter is presented in a clear orderly manner and typographical errors are few. The book is recommended by the reviewer as indispensible to students interested in sedimentary rocks. It is unfortunate that the price ($10.00) will probably limit extensive use of this book by beginners.

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Microscopic Determination of the Ore Minerals, M. N. Short, U. S. Geol. Survey Bull. 914, Washington, 1940. pp. 314, pls. 14; figs. 33, price $1.00.

This edition (second) has been enlarged by 110 pages over the first edition. Most of the material in the first edition has been retained and much new and important data have been added. The following are some of the new topics covered: mounting of specimen in bakelite, diamond, corundum, and silicon carbide saws, grinding and polishing machinery, various methods of sizing fine abrasives, principles of polishing and various methods employed, new methods and instruments for measuring reflectivity of minerals, and spectrographic methods for the identification of minerals.

The determinative tables and the microchemical section have been revised and the latter enlarged to include tests for many of the rarer elements such as platinum, palladium, ruthenium, germanium, etc. The new edition is essential to all students interested in the identification of ore minerals. Mr. Short is to be congratulated for the revision of this standard text and reference book.

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Petrology and Genesis of the Third Bradford Sand, by Paul D. Krynine, 134 pp., 37 figs. Bull. 29 of Mineral Industries Experiment Station, Pennsylvania State College Bulletin (1940).

As the title indicates, this work is a petrographic study of one of the sands encountered in drilling in the Bradford oil pool of northern Pennsylvania. The sand belongs to the upper Devonian. There are five chapters as follows: Introduction and General Geology, Mineralogy, Petrography, Texture and Pore Pattern, and Petrology and Origin of the Third Bradford Sand. The first, second and third chapters add little that would be different were any other sand described. The minerals and the rocks which they form are described in excellent detail. Chapter 4 presents data relating to porosity, permeability, pattern and dimensions of pores and similar data. The real contribution of the work is found in chapter 5 in which the sediments are interpreted, their sources are determined, the environmental condition to which they are due is suggested, and the setting of the third Bradford sand in the Paleozoic history of Appalachia and the Appalachian geosyncline is portrayed. A very illustrative diagram of the sources of the sediments in central and western Pennsylvania is presented in figure 3, p. 14. The work is valuable in that it shows the extent to which geologic history may be deciphered and paleogeography may be revealed from a study of sediments.

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Geology of Coal, by Otto Stutzer and Adolf C. Noé. Translated and revised by Adolf C. Noé. xiii+461 pages, 198 text figures, December, 1940. University of Chicago Press. Price $5.00.

This new work on coal is a translation and revision by the late Doctor Noé of the second edition of *Kohle*, 1923, by Otto Stutzer. The translation was nearly completed at the time of his recent death. Section C of Chapter IX—"The influence of coal beds on the geothermal gradient"—was translated by A. Gode-von Aesch, formerly of the University of Chicago. Doctor Noé also received assistance with parts of the translation from Doctor Gilbert Thiessen of Pittsburgh, Pa., and Doctor Gilbert H. Cady of the Geological Survey of Illinois assisted in the editorial work necessary for preparing the book for the press.

The book contains nine chapters as follows.

I Definition of coal, pp. 1–2
II Coal as a rock: Survey of the physical and chemical properties of coal, pp. 3–50
III The microscopic examination of coal, pp. 51–87
IV The origin of coal, 88–126
V The processing of coal, 127–131
VI Origin of coal beds, 132–183
VII Stratigraphy of coal deposits, 184–239
VIII The petrography of coal beds, 240–322
IX Disturbances of coal beds, 323–426

Each chapter is accompanied by a rather complete bibliography.

Some chapters are very short, as chapter I in which a definition of coal is given on two pages and chapter V which considers the processing of brown and bituminous coals on four pages.

Coal is defined as "a combustible rock which had its origin in the accumulation and partial decomposition of vegetation." Reasons for this definition are presented in subsequent chapters. The physical and chemical properties of coal, both micro-

scopic and macroscopic, are considered in much detail. The authors discuss the various factors producing transformation of vegetable matter into coal and they evidently accept the autochthonous origin for most coal deposits. The allochtonous theory of origin is given scant consideration. The stratigraphy, petrography, and structure of coal beds are rather exhaustively considered in three chapters and these three chapters account for nearly one half of the book.

There are some things in the book with which geologists may find themselves in disagreement. For example, on page 90 it is stated on the authority of H. Potonié —and the authors do not dissent for the statement—that stages in the decomposition of vegetable and animal substances are "disintegration, moldering, peat formation, and putrifaction." It is a new usage for the term disintegration to consider it a form of decomposition. Disintegration is said to "take place in the presence of oxygen and moisture and may be regarded as a slow combustion of organic substance. No residue of carbon compounds is left. Only volatile substances are produced, namely, carbon dioxide and water." The processes involved in this destruction of organic matter seem to be entirely chemical. Designation of chemical processes as disintegration is very contrary to the current use of the term.

There are places in the book where a somewhat careless use of words obtains. The subject of fusain is considered on pages 108 to 113. This is designated "fossil charcoal" in the heading, but in the discussion, in addition to fosain, two other terms, charcoal and wood charcoal, are used. Moreover, they are used without any system for the same substance. As an example it is stated, "Anthracite, bituminous coal, and brown-coal sometimes contain fossil charcoal. It is strange that fusain is more common in bituminous coals than in brown coals." An uninformed reader would be confused and might conclude that "fossil charcoal" is a different substance than "fusain." The terms should have been defined in the beginning of the topic and one selected for use throughout.

Reading of the book left with the reviewer the impression that the authors were hesitant to take positive positions. There are many statements of what others have shown, but the authors seem to hesitate to express preference for one of several explanations.

The reviewer considers the new work a valuable contribution to the literature on the geology of coal, particularly as it introduces to American students the views relating to coal that are held by Continental European geologists. That Doctor Noé approached the subject from the point of view of a paleobotanist is also a contribution.

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Coal. Its Properties, Analysis, Classification, Geology, Extraction, Uses and Distribution. Elwood S. Moore. 2nd edition, ix+473 pages, 20 plates and 151 text figures. John Wiley and Sons, New York City.

The first edition of this valuable work was published in 1921. The second edition brings it up to date with respect to the petrology and chemistry of coal, and the technology dealing with classification, methods of prospecting, estimation of reserves, extraction, preparation for market, and utilization. The structure of the book has not been changed and there has been an increase of only 10 pages. Seven of the 15 chapters have been lengthened from one to 10 pages, the greatest increases being in Chapter I dealing with the physical properties of coal and Chapter X which considers the mining of coal. Seven chapters have been shortened from one to nine pages, the greatest shortening being in Chapter IX dealing with prospecting for coal and the valuation of coal lands. Chapters XII to XV on the coal resources of the world have been little changed, the reason given being that no recent extensive reports on the coal resources of the world have been published.

Some changes should doubtless have been made. For instance, statements respecting the coal of Newfoundland are only slightly modified from those of the first edition notwithstanding Hayes and Johnson's cautious remarks respecting the doubtful character of the coal resources of southwest Newfoundland (Bull. no. 12, 1938, Geol. Survey Newfoundland).

The book by Doctor Moore is supplementary to that by Doctor Noé. The approaches of the two men are different. Doctor Moore is an economic geologist, Doctor Noé a paleobotanist. Doctor Moore emphasizes the classification, prospecting, mining, and uses of coal and the world's resources of this material in 231 pages, a little more than one half the book, whereas these subjects are hardly considered by Doctor Noé. Students interested in coal should read both books as each to some degree is a supplement to the other.

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Some Principles of Accelerated Stream and Valley Sedimentation: by Stafford C. Happ, Gordon Rittenhouse and G. C. Dobson. *United States Department of Agriculture Technical Bulletin no. 695.* Pp. 134; 16 plates, 19 figures, 11 tables. Washington, 1940 (United States Government Printing Office, Superintendent of Documents; 75 cents, paper cover).

A technical bulletin of the Soil Conservation Service, this paper is a summary of detailed studies of stream and valley sedimentation in the drainage basins of Tobitubby and Hurricane Creeks in Lafayette County, Miss. The influence of culturally accelerated soil erosion on the sedimentation within these basins is fully discussed.

The bulletin is divided into two main parts of which the first is a description of the conditions in the valleys named and their tributary drainage areas. The deposition of harmful sediments is the major important destructive effect of erosion in the areas studied and this is considered as probably the case for other areas as well. The textures of the sediments are important factors in determining the extent of the damage. The damages directly due to excessive sedimentation are three.

First, increasing frequency and height of overbank floods resulting from sedimentary filling of stream channels and aggradation of flood-plain surfaces. It is estimated that about 46 percent of the bottom lands of the two drainage basins is uncultivated because of the danger of floods.

Second, swamping of valley lands as a result of obstructed surface run-off and the rising ground water table caused by aggradation of the stream beds. Swamping as a result of excessive sedimentation is estimated to have affected 8 per cent of the total bottom lands of the two drainage areas.

Third, sand deposition on the former silt loam bottom lands, with consequent loss in the productive capacity of the land. The total area of sanding in the two drainage areas is about 20 per cent of the bottom lands. Direct damage also results from (1) valley trenching in the headwater areas and (2) streambank erosion.

As a result of these studies, 45 statements of fact have been listed as tentative "principles," with an explanatory discussion directly following each principle. The purposes of the principles are: (1), to verify and elucidate the controlling physical principles that govern excessive stream and valley sedimentation, and (2), to evaluate the major factors in the complex interrelationship between stream and valley sedimentation and soil erosion, so that there may be a sound scientific basis for planning alleviation and protection of valley resources from excessive stream and valley sedimentation.

The same basic fact often underlies more than one principle. They are grouped under eight headings as follows: (1), significance of criteria for recognition of modern valley sediments; (2), types,

characters and distribution of modern valley sediments; (3), erosional processes as factors in excessive sedimentation; (4), valley sedimentation as a measure of upland erosion; (5), damages resulting from culturally accelerated valley sedimentation; (6), indications of future trends in stream and valley sedimentation; (7), relation of stream and valley sedimentation to flood-control problems; and (8), relation of sedimentation control to soil conservation.

The authors state that these principles are intended more as practical considerations in the field of stream and valley sedimentation problems, than as statements of basic natural laws. They consider them as a stage in the understanding of such problems, to be tested and revised until a definite summary of the most important facts in the field emerges. Their work constitutes an important advance in this direction, and it is to be hoped that the testing and revision they desire be not too long delayed.

The bulletin contains a very complete bibliography with references to erosional and depositional problems in other areas.

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